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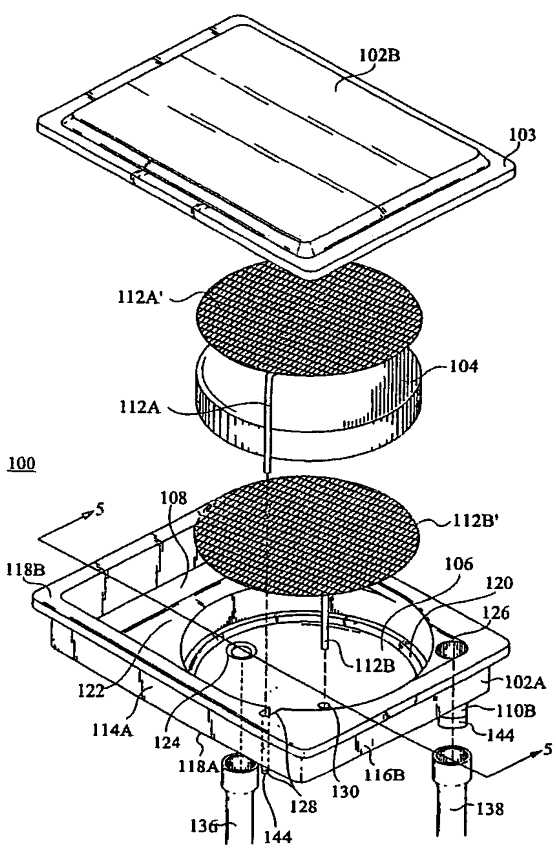
(54) Title: METHOD AND APPARATUS FOR LOW-COST ELECTROKINETIC PUMP MANUFACTURING



(57) Abstract: An electroosmotic pump (22) used in a closed loop cooling system (10). The pump includes a fluid chamber, a pumping element (104), an inlet electrode (1 12A), an outlet electrode (112B), and means for providing electrical voltage to the inlet electrode and the outlet electrode to produce an electrical field therebetween. The pumping element is configured to pump fluid therethrough, and the pumping element is positioned to segment the fluid chamber into an inlet chamber (142) including a fluid inlet port (126) and an outlet chamber (140) including a fluid outlet port (124). The size of the inlet chamber is proportional to a predetermined residence time of the inlet chamber. The inlet electrode is positioned within the inlet chamber and a predetermined distance from the first surface of the pumping element. The outlet electrode is positioned within the outlet chamber and a predetermined distance from a second surface of the pumping element.

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B. FIELDS SEARCHED

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U.S. : 417/48,50.cols.

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 3,923,426 (THHEUEWS) 2 December 1975 (02.12.1975), Abstract Figure 1 and 2, columns 1-7.	1-115 --- 15, 17-20, 22, 23, 25, 47, 49, 50, 52, 54, 55, 57, 56, 80, 82-89
Y	US 5,901,037 (HAMILTON et al.) 04 May 1999 (04.05.1999) Figure 1-5.	116-119
Y	US 6,388,285 (MCGINN et al.) 14 May 2002 (17.05.2002), column 1 lines 50-65.	15, 18, 19, 20, 23, 25, 47, 50, 52, 55, 57, 80, 85, 86-90
Y	US 5,685,966 (AARON et al.) 11 November 1997 (11.11.1997), column 5 lines 25-32.	15, 17, 18, 19, 22, 23, 47, 49, 50, 54, 55, 56, 80, 82-84, 87-89
Y	US 6,154,226 (YORK et al) 28 November 2000 (28.11.2000), column 9, line 54, Figure 6.	9-11, and 42

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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Name and mailing address of the ISA/US	Authorized officer
Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450 Alexandria, Virginia 22313-1450 Facsimile No. (703) 305-3230	Timothy S. Thorpe Telephone No. (571) 272-4832

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INTERNATIONAL SEARCH REPORT

C. (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X — P	US 220030062149 A1 (GOODSON et al.) 03 April 2003 (03.04.2003), Abstract, paragrpahs 17, 70-86.	1-119 — 1-119
A	US 6,443,704 B1 (DARABI et al.) 03 September 2002 (03.09.2002), full document.	1-119
A	US 6,719,535 B2 (RAKESTRAW et al.) 13 April 2004 (13.04.2004), full document.	1-119
Y	US 6,260,579 B1 (YOKOTA et al.) 17 July 2001 (17.07.2001), column 13, line 64.	14
Y	US 6,251,254 B1 (KATOH et al) 26 June 2001 (26.06.2001), see Abstract.	18, 19, 23, and 24

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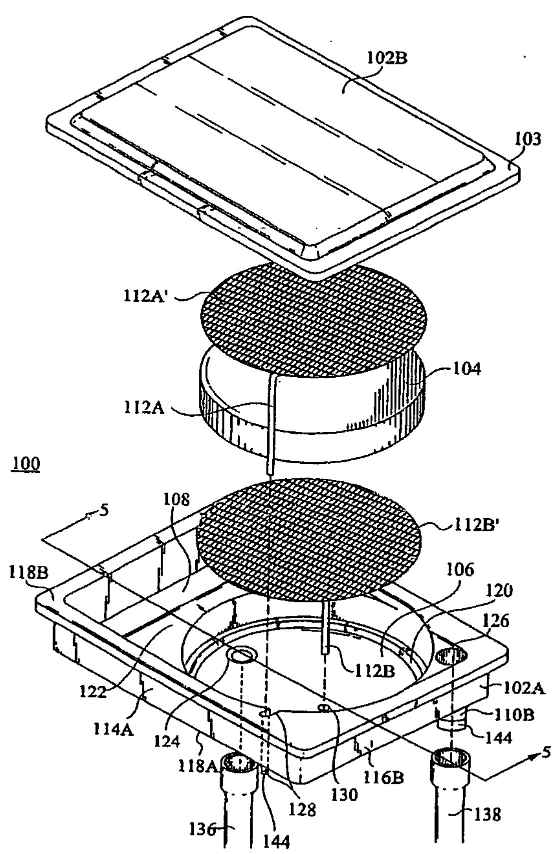

(57) Abstract: An electroosmotic pump used in a closed loop cooling system. The pump includes a fluid chamber, a pumping element, an inlet electrode, an outlet electrode, and means for providing electrical voltage to the inlet electrode and the outlet electrode to produce an electrical field therebetween. The pumping element is configured to pump fluid therethrough, and the pumping element is positioned to segment the fluid chamber into an inlet chamber including a fluid inlet port and an outlet chamber including a fluid outlet port. The size of the inlet chamber is proportional to a predetermined residence time of the inlet chamber. The inlet electrode is positioned within the inlet chamber and a predetermined distance from a first surface of the pumping element. The outlet electrode is positioned within the outlet chamber and a predetermined distance from a second surface of the pumping element.

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GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

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METHOD AND APPARATUS FOR LOW-COST ELECTROKINETIC PUMP MANUFACTURING

Related Applications

This Patent Application claims priority under 35 U.S.C. 119 (e) of the co-pending U.S. Provisional Patent Application, Serial No. 60/444,269, filed January 31, 2003 and entitled "REMEDIES FOR FREEZING IN CLOSED-LOOP LIQUID COOLING FOR ELECTRONIC DEVICES". The co-pending U.S. Provisional Patent Application, Serial No. 60/444,269, filed January 31, 2003 and entitled "REMEDIES FOR FREEZING IN CLOSED-LOOP LIQUID COOLING FOR ELECTRONIC DEVICES" is hereby incorporated by reference.

Field of the Invention

The invention relates to a method and apparatus for cooling a heat producing device in general, and specifically, to a cost-effective electrokinetic pump assembly and method of manufacturing thereof.

Background of the Invention

Electrokinetic pumps are capable of generating flowrates in excess of 100 mL/min and pressures in excess of 10 PSI. As known in the art, electrokinetic pumps operate by applying a voltage to electrodes positioned on opposite sides of a porous pumping element within a housing. Prior art electrokinetic pumps are contained within housings, some of which have design disadvantages. These disadvantages impair consistent performance of the pump as well as diminish the reliability of the pump. In particular, the different thermal expansion coefficients of the array of materials used in existing electrokinetic pumps can cause leakage problems and feedthrough failure. In addition, prior art electrokinetic pumps do not take into consideration the mismatch of thermal expansion between the material of the pump housing and the fluid ports as well as fluid lines attached to the pump housing. Such a mismatch in thermally expansive materials may cause leakage or breakage between the pump and fluid lines. Prior art electrokinetic pump housings which attempt to rectify these problems have complex designs which makes manufacturing of the pump expensive, time consuming and labor-intensive.

Further, physical design configurations of prior art electrokinetic pumps does not promote optimal use. In particular, specifications for fluid chamber sizes and positions of the

pumping elements, and their electrodes, can be improved to better optimize the performance of the electrokinetic pump.

What is needed is a sealed pump housing having a design configuration which rectifies these disadvantages and is manufacturable in a cost effective manner.

Summary of the Invention

One aspect of the present invention includes an electroosmotic pump comprising a fluid chamber, a pumping element for pumping fluid therethrough, the pumping element positioned to segment the fluid chamber into an inlet chamber including a fluid inlet port and an outlet chamber including a fluid outlet port, an inlet electrode positioned within the inlet chamber and a predetermined distance from a first surface of the pumping element, an outlet electrode positioned within the outlet chamber, and means for providing electrical voltage to the inlet electrode and the outlet electrode to produce an electrical field therebetween, wherein the means for providing is coupled to the inlet electrode and the outlet electrode. The predetermined distance that the inlet electrode is positioned from the first surface can be in a range of about 0.05 mm to about 5.0 mm. The outlet electrode can be positioned a predetermined distance from a second surface of the pumping element. The predetermined distance that the outlet electrode is positioned from the second surface can be in a range of about 0.05 mm to about 5.0 mm. The outlet electrode can be positioned on a second surface of the pumping element. A residence time of the inlet chamber is in a range of about 1/20 of a minute to about 1 minute. A volume of the inlet chamber can be equal to an area of the pumping element multiplied by a width of between about 0.4 cm and about 3.0 cm. The electroosmotic pump can be manufactured using one or more materials comprising metal, glass, ceramic, plastic, or a combination thereof. The one or more materials can be coupled by one or more sealing materials. The one or more sealing materials can comprise solder, sealing glass, low modulus adhesives, or a combination thereof. Low modulus adhesives can seal the pumping element to a housing of the electroosmotic pump. The electroosmotic pump can be manufactured using one or more pump materials such that each pump material is compatible with the fluid, or such that the one or more pump materials that are not compatible with the fluid are overcoated with a compatible material. The fluid can comprise a buffered water solution. The one or more pump materials can comprise insulating materials that are compatible with buffered water solutions. The pump material can be selected from a group consisting of silicon nitride, titania, alumina, silica, borosilicate, vycor, and plastic. The pumping element can exhibit a negative zeta potential in the presence of the fluid and the

inlet electrode is an anode electrode and the outlet electrode is a cathode electrode. The pumping element can exhibit a positive zeta potential in the presence of the fluid and the inlet electrode is a cathode electrode and the outlet electrode is an anode electrode. A material of the anode electrode can be selected from the group consisting of platinum, platinum clad niobium, platinum plated titanium, platinum clad tantalum, graphite, glassy carbon, mixed metal oxide coating on titanium, silver-impregnated ink, and dimensionally-stable anode material. The mixed metal oxide coating on titanium can include an iridium and tantalum oxide coating on titanium. The dimensionally-stable anode material can include one from the group consisting of conducting iridium oxide coating on titanium and ruthenium oxide coating on titanium. A material of the cathode electrode can be selected from a group consisting of platinum, copper, platinum plated titanium, stainless steel, graphite, gold, plated silver, silver-impregnated ink, and glassy carbon. The electroosmotic pump can include one or more inlet chambers, one or more pumping elements, and one or more outlet chambers, wherein each inlet chamber includes one or more fluid inlet ports. The electroosmotic pump can also include a recombination chamber coupled to the inlet chamber to recombine an inlet chamber gas and an outlet chamber gas. The inlet port to the inlet chamber can be configured and positioned such that fluid entering the inlet chamber becomes well mixed. The fluid can be well mixed by providing the fluid from the inlet port into the inlet chamber at a high average velocity. The high average velocity of the fluid entering the inlet chamber at the inlet port can be greater than about 25 centimeters per second.

In another aspect of the present invention, an electroosmotic pump comprises a fluid chamber, a pumping element for pumping fluid therethrough, the pumping element positioned to segment the fluid chamber into an inlet chamber including a fluid inlet port and an outlet chamber including a fluid outlet port, wherein a size of the inlet chamber is proportional to a predetermined residence time of the inlet chamber, an inlet electrode positioned within the inlet chamber, an outlet electrode positioned within the outlet chamber, and means for providing electrical voltage to the inlet electrode and the outlet electrode to produce an electrical field therebetween, wherein the means for providing is coupled to the inlet electrode and the outlet electrode. The residence time of the inlet chamber can be in a range of about 1/20 of a minute to about 1 minute. A volume of the inlet chamber can be equal to an area of the pumping element multiplied by a width of between about 0.4 cm and about 3.0 cm. The inlet electrode can be positioned a predetermined distance from a first surface of the pumping element. The predetermined distance that the inlet electrode is positioned from the first surface can be in a range of about 0.05 mm to about 5.0 mm. The

outlet electrode can be positioned a predetermined distance from a second surface of the pumping element. The predetermined distance that the outlet electrode is positioned from the second surface can be in a range of about 0.05 mm to about 5.0 mm. The outlet electrode can be positioned on a second surface of the pumping element. The electroosmotic pump can consist of one or more materials that are non-reactive to oxygen. The electroosmotic pump can be manufactured using one or more materials comprising metal, glass, ceramic, plastic, or a combination thereof. The one or more materials can be coupled by one or more sealing materials. The one or more sealing materials can comprise solder, sealing glass, low modulus adhesives, or a combination thereof. Low modulus adhesives can seal the pumping element to a housing of the electroosmotic pump. The electroosmotic pump can be manufactured using one or more pump materials such that each pump material is compatible with the fluid, or such that the one or more pump materials that are not compatible with the fluid are overcoated with a compatible material. The fluid can comprise a buffered water solution. The one or more pump materials can comprise insulating materials that are compatible with buffered water solutions. The pump material can be selected from a group consisting of silicon nitride, titania, alumina, silica, borosilicate, vycor, and plastic. The pumping element can exhibit a negative zeta potential in the presence of the fluid and the inlet electrode is an anode electrode and the outlet electrode is a cathode electrode. The pumping element can exhibit a positive zeta potential in the presence of the fluid and the inlet electrode is a cathode electrode and the outlet electrode is an anode electrode. A material of the anode electrode can be selected from the group consisting of platinum, platinum clad niobium, platinum plated titanium, platinum clad tantalum, graphite, glassy carbon, mixed metal oxide coating on titanium, silver-impregnated ink, and dimensionally-stable anode material. The mixed metal oxide coating on titanium can include an iridium and tantalum oxide coating on titanium. The dimensionally-stable anode material can include one from the group consisting of conducting iridium oxide coating on titanium and ruthenium oxide coating on titanium. A material of the cathode electrode can be selected from a group consisting of platinum, copper, platinum plated titanium, stainless steel, graphite, gold, plated silver, silver-impregnated ink, and glassy carbon. The electroosmotic pump can include one or more inlet chambers, one or more pumping elements, and one or more outlet chambers, wherein each inlet chamber includes one or more fluid inlet ports. The electroosmotic pump can further comprise a recombination chamber coupled to the inlet chamber to recombine an inlet chamber gas and an outlet chamber gas. The inlet port to the inlet chamber can be configured and positioned such that fluid entering the inlet chamber becomes well mixed.

The fluid can be well mixed by providing the fluid from the inlet port into the inlet chamber at a high average velocity. The high average velocity of the fluid entering the inlet chamber at the inlet port can be greater than about 25 centimeters per second.

In yet another aspect of the present invention, an electroosmotic pump comprises a fluid chamber, a pumping element for pumping fluid therethrough, the pumping element positioned to segment the fluid chamber into an inlet chamber including a fluid inlet port and an outlet chamber including a fluid outlet port, a gas permeable element to allow passage of a gas from the outlet chamber to the inlet chamber while preventing the passage of the fluid therethrough, an inlet electrode positioned within the inlet chamber and a predetermined distance from a first surface of the pumping element, an outlet electrode positioned within the outlet chamber, and means for providing electrical voltage to the inlet electrode and the outlet electrode to produce an electrical field therebetween, wherein the means for providing is coupled to the inlet electrode and the outlet electrode. The gas permeable element can allow the passage of an outlet chamber gas from the outlet chamber to the inlet chamber. The outlet chamber gas can be predominately hydrogen. The outlet chamber gas can be predominately oxygen. The predetermined distance that the inlet electrode is positioned from the first surface can be in a range of about 0.05 mm to about 5.0 mm. The outlet electrode can be positioned a predetermined distance from a second surface of the pumping element. The predetermined distance that the outlet electrode is positioned from the second surface can be in a range of about 0.05 mm to about 5.0 mm. The outlet electrode can be positioned on a second surface of the pumping element. A residence time of the inlet chamber is in a range of about 1/20 of a minute to about 1 minute. A volume of the inlet chamber can be equal to an area of the pumping element multiplied by a width of between about 0.4 cm and about 3.0 cm. The electroosmotic pump can be manufactured using one or more materials comprising metal, glass, ceramic, plastic, or a combination thereof. The one or more materials can be coupled by one or more sealing materials. The one or more sealing materials can comprise solder, sealing glass, low modulus adhesives, or a combination thereof. Low modulus adhesives can seal the pumping element to a housing of the electroosmotic pump. The electroosmotic pump can be manufactured using one or more pump materials such that each pump material is compatible with the fluid, or such that the one or more pump materials that are not compatible with the fluid are overcoated with a compatible material. The fluid can comprise a buffered water solution. The one or more pump materials can comprise insulating materials that are compatible with buffered water solutions. The pump material can be selected from a group consisting of silicon nitride,

titania, alumina, silica, borosilicate, vycor, and plastic. The pumping element can exhibit a negative zeta potential in the presence of the fluid and the inlet electrode is an anode electrode and the outlet electrode is a cathode electrode. The pumping element can exhibit a positive zeta potential in the presence of the fluid and the inlet electrode is a cathode electrode and the outlet electrode is an anode electrode. A material of the anode electrode can be selected from the group consisting of platinum, platinum clad niobium, platinum plated titanium, platinum clad tantalum, graphite, glassy carbon, mixed metal oxide coating on titanium, silver-impregnated ink, and dimensionally-stable anode material. The mixed metal oxide coating on titanium can include an iridium and tantalum oxide coating on titanium. The dimensionally-stable anode material can include one from the group consisting of conducting iridium oxide coating on titanium and ruthenium oxide coating on titanium. A material of the cathode electrode can be selected from a group consisting of platinum, copper, platinum plated titanium, stainless steel, graphite, gold, plated silver, silver-impregnated ink, and glassy carbon. The electroosmotic pump can include one or more inlet chambers, one or more pumping elements, and one or more outlet chambers, wherein each inlet chamber includes one or more fluid inlet ports. The electroosmotic pump can also include a recombination chamber coupled to the inlet chamber to recombine an inlet chamber gas and an outlet chamber gas. The inlet port to the inlet chamber can be configured and positioned such that fluid entering the inlet chamber becomes well mixed. The fluid can be well mixed by providing the fluid from the inlet port into the inlet chamber at a high average velocity. The high average velocity of the fluid entering the inlet chamber at the inlet port can be greater than about 25 centimeters per second.

Other features and advantages of the present invention will become apparent after reviewing the detailed description of the preferred embodiments set forth below.

Brief Description of the Drawings

Figure 1 illustrates a schematic diagram of a closed loop cooling system in accordance with the present invention.

Figure 2A illustrates an exploded view of the pump assembly in accordance with the preferred embodiment of the present invention.

Figure 2B illustrates an exploded view of a pump assembly in accordance with an alternative embodiment of the present invention.

Figure 3A illustrates a front side view of the bottom housing portion in accordance with the preferred embodiment of the present invention.

Figure 3B illustrates a front side view of the bottom housing portion in accordance with the alternative embodiment of the present invention.

Figure 4A illustrates a back side exploded view of the bottom housing portion in accordance with preferred embodiment of the present invention.

Figure 4B illustrates a back side exploded view of the bottom housing portion in accordance with the alternative embodiment of the present invention.

Figure 5A illustrates a cross sectional view of the pump assembly in accordance with the preferred embodiment of the present invention.

Figure 5B illustrates a cross sectional view of an alternative pump assembly in accordance with the alternative embodiment of the present invention.

Figure 6A illustrates a cross sectional view of the electrical contacts used in the preferred pump assembly in accordance with the present invention.

Figure 6B illustrates a cross sectional view of the electrical contacts used in the alternative pump assembly in accordance with the present invention.

Figure 7A illustrates a cut-away view of the preferred pumping element with electrical contact positioned a predetermined distance therefrom in accordance with the present invention.

Figure 7B illustrates a cut-away view of the preferred pumping element with electrical contact coupled thereto in accordance with the present invention.

Figure 8 illustrates a cross sectional view of another alternative pump assembly in accordance with the present invention.

Detailed Description of the Present Invention

Figure 1 illustrates a schematic diagram of a closed loop cooling system 10 in accordance with the present invention. The cooling system preferably includes a microchannel heat exchanger 12 coupled to a heat source 99, such as a microprocessor. Alternatively, the heat exchanger 12 is integrally formed with the heat source 99 as one component. It should be noted that the system 10 incorporates any type of heat exchanger.

As shown in Figure 1, the outlet fluid port 16 of the heat exchanger 12 is coupled to the fluid line 18 which is coupled to the inlet fluid port 24 of the heat rejecter 20. The outlet fluid port 26 of the heat rejecter 20 is coupled to the fluid line 18 which is coupled to the fluid inlet port 28 of the pump 22 of the present invention. The outlet fluid port 30 of the pump 22 is coupled to the fluid line 18 which is coupled to the fluid inlet port 14 of the heat exchanger 12. The pump 22 of the present invention pumps and circulates fluid within the

closed loop 10. In one embodiment, the present circulation system 10 includes more than one heat exchanger 12. In another embodiment, the present circulation system 10 includes more than one heat rejecter 20. It is also contemplated that more than one heat source 99 can be cooled within the circulation system 10. Alternatively, multiple pumps (not shown) circulate fluid to their respective inlet and outlet ports 14, 16, 24, 26 in the event there are more than one heat exchanger 12 and more than one heat rejecter 20. It is apparent to one skilled in the art that other components not shown in Figure 1 are contemplated. It is also apparent to one skilled in the art that the components of the system 10 can be placed in any other appropriate order in the loop 10 and the order is not limited to the configuration shown in Figure 1.

Preferred operation of the circulation system 10 involves cooling the heat source 99, whereby the pump 22 circulates cooled fluid through its outlet port 30 to the heat exchanger 12. The pump 22 of the present invention preferably circulates a uniform flow to the heat exchanger 12 and heat rejecter 20 and is configured to pump fluid undergoing either one or two phase flow within the system 10 depending upon circumstances. Alternatively, the pump 22 can vary the flow to the heat exchanger 12. The fluid exiting from the pump 22 enters the heat exchanger 12 and absorbs the heat generated by the heat source 99. Within the heat exchanger 12, the fluid experiences either single or two phase flow depending on a variety of factors, including but not limited to the amount of heat generated by the heat source 99, the amount and flow rate of the fluid through the heat source as well as other factors. The heated fluid exits the heat exchanger 12 through the outlet port 16 and enters the inlet port 24 of the heat rejecter 20, whereby the heat rejecter 20 releases the heat within the fluid into the surrounding air and cools the fluid. The cooled fluid exits the heat rejecter 20 via the outlet port 26 and enters the pump 22 via the inlet port 28. This process continues to keep the overall system 10 or heat source 99 operating at a desired maximum temperature. Alternatively, this process continues to keep each of more than one individual components in the system 10 operating at desired temperatures.

The fluid in the cooling system 10 is preferably water-based. Alternatively, the fluid in the system 10 is a combination of organic solutions which provide a low freezing temperature or enhanced thermal characteristics, as well as resistance to corrosion. The fluid within the system can exhibit a single-phase liquid state or two phase flow. The two phase flow includes a fluid which is both liquid as well as vapor states. However, whether a single-phase or a two-phase system, it is apparent to one skilled in the art that at equilibrium and at all operating or storage temperatures, the fluid will exhibit some vapor in the loop 10 as well

as the components such as tubes, heat exchangers, pumps, manifolds, fittings and connectors.

Figure 2A illustrates an exploded view of a pump assembly in accordance with the preferred embodiment of the present invention. As shown in Figure 2A, a preferred pump 100 includes a housing body having a bottom housing portion 102A and a housing lid 102B. In addition, the pump 100 includes a fluid inlet port 126 and a fluid outlet port 124 as well as an outlet electrode 112B' and an inlet electrode 112A'. The outlet electrode 112B' is coupled to an outlet electrical contact 112B, and the inlet electrode 112A' is coupled to an inlet electrical contact 112A. The outlet electrical contact 112B and the inlet electrical contact 112A each preferably coupled to the pump 100 through the bottom housing portion 102A. The bottom housing portion 102A preferably includes a cavity 106 which holds an electroosmotic pumping element 104 within. According to the preferred embodiment, the pumping element 104 is a glass frit. The bottom portion 102A also includes a recombination cavity 108 which serves to recombine hydrogen and oxygen formed within the cooling system into water. The theory of how hydrogen and oxygen is formed within the pump due to electroosmosis is well known in the art and will not be discussed in more detail herein. If a liquid other than the water is pumped, it will be understood that other gases or chemicals can be formed.

The outlet electrode 112B' and the inlet electrode 112A' are each preferably spaced a predetermined distance from the pumping element 104. In this preferred case, the outlet electrode 112B' and the inlet electrode 112A' are referred to as off-frit electrodes. Preferably, the inlet electrode 112A' is mechanically coupled to but electrically insulated from the housing 102A, and the outlet electrode 112B' is mechanically coupled to but electrically insulated from the bottom surface of the cavity 106 within the housing portion 102A. Both electrodes are preferably coupled to the housing 102A. The inlet electrode 112A' is either coupled to the housing 102A directly or coupled via an intermediate support structure. Irrespective of the manner in which the inlet electrode 112A' is coupled to the housing 102A, the inlet electrode 112A' is positioned a predetermined distance from the corresponding nearest surface of the pumping element 104 (top surface of the pumping element 104 in Figure 2A). The predetermined distance between the inlet electrode 112A' and the pumping element 104 is preferably within a range of about 0.05 mm to about 5.0 mm. Similarly, the outlet electrode 112B' is either coupled to the housing portion 102A directly or coupled via an intermediate support structure. The outlet electrode 112B' is preferably positioned a predetermined distance from the corresponding nearest surface of the pumping element 104 (bottom surface of the pumping element 104 in Figure 2A). The

predetermined distance between the outlet electrode 112B' and the pumping element 104 is preferably within a range of about 0.05 mm to about 5.0 mm.

The inlet electrode 112A' and the outlet electrode 112B' can be a wire mesh, a perforated foil, a loose spiral, clad metal foils, expanded metal foils, or a film deposited on the inner surface of the housing portion. Other types of electrodes can also be used as the inlet electrode 112A' and the outlet electrode 112B'. Examples of such alternative electrodes are described in the co-filed, co-pending and co-owned U.S. Patent Application Serial No. 10/669,495, filed on September 23, 2003, entitled "Micro-fabricated Electrokinetic Pump with On-Frit Electrode", which is hereby incorporated by reference. The material used for an anode electrode is preferably selected from the group consisting of platinum, platinum clad niobium, platinum plated titanium, platinum clad tantalum, graphite, glassy carbon, mixed metal oxide coating on titanium such as iridium and tantalum oxide coating on titanium, silver-impregnated ink, and dimensionally-stable anode material such as conducting iridium oxide or ruthenium oxide coating on titanium. The material used for a cathode electrode is preferably selected from the group consisting of platinum, copper, platinum plated titanium, stainless steel, graphite, gold, plated silver, silver-impregnated ink, and glassy carbon.

Figure 2B illustrates an exploded view of a pump assembly in accordance with an alternative embodiment of the present invention. As shown in Figure 2B, an alternative pump 200 includes a housing body having a bottom housing portion 202A and a housing lid 202B. The pump 200 is identical to the pump 100 with the exception that an outlet electrode 212B' and an inlet electrode 212A'are coupled to the pumping element 204. In this alternative case, the outlet electrode 212B' and the inlet electrode 212A' are referred to as on-frit electrodes.

Figure 3A illustrates a perspective frontal view of the receiving area of the bottom housing portion 102A in accordance with the preferred embodiment of the present invention. In addition, Figure 4A illustrates a perspective rear exploded view of the outer surface of the bottom housing portion 102A in accordance with the preferred embodiment of the present invention. As shown in Figures 3A and 4A, the preferred bottom housing portion 102A includes a bottom surface 118A, side walls 114A, 114B, 116A, 116B. A top lip 118B is formed peripheral with the sidewalls 114A, 114B, 116A, and 116B around the entire bottom housing portion 102A. The top lip 118B is shaped to align with and attach to the outer lip 103 (Figure 2A) of the housing lid 102B. As shown in Figure 5A, the lip 103 of the housing lid 102B and the top lip 118B of the bottom housing 102A create a seal when bonded or mated in contact with one another, thereby forming a sealed environment within the pump

100. Although the side walls 114A, 114B, 116A, and 116B preferably form a rectangular housing portion 102A, it is apparent to one skilled in the art that the rectangular housing portion can have any other appropriate shape (e.g. circular, square, trapezoidal, any other polygon, or combinations of parts of a circle and a polygon).

Referring back to Figure 3A, the bottom housing portion 102A has the receiving cavity 106 and the recombination cavity 108, whereby a barrier wall 122 is positioned therebetween to separate a portion of the receiving cavity 106 from the recombination cavity 108. Preferably, the receiving cavity 106 is circular in shape, such that a circular electroosmotic pumping element 104 fits securely within. Preferably, the shape of the outlet electrode 112B' and the inlet electrode 112A' (not shown in Figure 3A) substantially matches the shape of the pumping element 104. Alternatively, the shape of the inlet electrode 112A' and the outlet electrode 112B' do not match the shape of the pumping element 104. Although the electroosmotic pumping element 104 (Figures 2A and 3A) has a circular disk-shape, other pumping element shapes are contemplated. Thus, the cavity 106 alternatively has a shape corresponding with the shape of the pumping element 104.

Figure 3B illustrates a perspective frontal view of the receiving area of the bottom housing portion 202A in accordance with the alternative embodiment of the present invention illustrated in Figure 2B. In this alternative embodiment, the outlet electrode 212B' and the inlet electrode 212A' are coupled to the pumping element 204, in other words the outlet electrode 212B' and the inlet electrode 212A' are on-frit electrodes. As such, the outlet electrode 212B' is not coupled to the bottom housing portion 202A. Since Figure 3B illustrates the bottom housing portion 202A, the inlet electrode 212A' is not shown in Figure 3B.

As shown in Figures 2A and 3A, the cavity 106 preferably includes a beveled edge 120 in the interior bottom surface. The pumping element 104 and housing 102 are preferably made of borosilicate glass, whereby both have a matching coefficient of thermal expansion (CTE) value. Therefore, the pumping element 104 as well as the housing 102 thermally expand at the same rate during operation. The bottom surface of the pumping element 104 sits on the edge 120 to create an outlet chamber 140 (Figure 5A) below the pumping element 104 and an inlet chamber 142 (Figure 5A) above the pumping element 104. The pumping element 104 is coupled to the edge 120 preferably by sealing glass, whereby fluid in the inlet chamber 142 is pumped through the pumping element 104. Alternatively, the pumping element 104 is coupled to the edge 120 by an adhesive or preferably a low modulus adhesive.

As shown in Figures 3A and 4A, the bottom housing portion 102A includes an inlet port 126 and an outlet port 124 preferably extending away from the outer bottom surface 118A of the bottom housing portion 102A. It is preferred that the fluid inlet port 126 and the fluid outlet port 124 extend from the same surface in the housing to allow the pump 100 to be placed in a small space. Alternatively, the inlet and outlet ports 126, 124 are configured to extend from different surfaces of the pump 100 housing. Referring to Figures 3A and 4A, the inlet port 126 leads into the cavity 106 and is in communication with the inlet fluid chamber 142. In addition, the inlet port 126 extends from the bottom surface 118A through the bottom housing portion 102A to the opening near the lip 118B of the bottom housing portion 102A. Fluid traveling through the inlet port 126 is kept separate from the fluid which travels through the outlet port 124. In addition, it is apparent to one skilled in the art that although only one inlet and one outlet port are shown and described herein, any number of inlet and outlet ports and fluid lines are alternatively used with the pump 100 of the present invention.

The orientation of the pump is an important factor to consider when choosing the location of the outlet port 124. In the preferred embodiment, the pumping element has a negative zeta potential. As such, the outlet electrode 112B' in the outlet chamber 140 (Figure 5A) generates H_2 gas during the operation of the electrokinetic pump. The H_2 gas eventually reaches the inlet chamber 142 (Figure 5A) of the pump in order to recombine with the O_2 at the catalyst to regenerate H_2O. A preferred arrangement of the pump 100, as shown in Figure 5A, includes the inlet port 126 positioned at or near the top of the inlet chamber 142. This configuration allows bouyancy to assist in the movement of the H_2 bubbles from the outlet electrode 112B' to the outlet port 124, whereby the H_2 bubbles are pushed through the fluid loop back to the inlet chamber 142 of the pump 100 and are recombined at the recombination chamber 108. Due to this effect, the pump 100 is oriented such that the recombination chamber 108 is positioned above the pump element 104.

Figure 5A illustrates a cross sectional view of the preferred pump assembly 100 in accordance with the present invention. The pumping element 104 sits on the edge 120 to form the outlet chamber 140 below the pumping element 104 and the inlet chamber 142 above the pumping element 104. The chamber that includes the inlet electrode is referred to as the inlet chamber, which in Figure 5A also corresponds to the inlet chamber 142. The chamber that includes the outlet electrode is referred to as the outlet chamber, which in Figure 5A also corresponds to the outlet chamber 140. The size of the inlet chamber is preferably configured according to a predetermined residence time. The residence time is defined as the volume of the inlet chamber divided by the flow rate. For example, if the inlet

chamber has a volume of 1 liter and the flow rate is 1 liter/minute, than the average residence time is 1 minute. In the preferred embodiment, the residence time is in a range of about 1/20 of a minute to about 1 minute. The configured volume of the inlet chamber scales with the anticipated flow rate of the pump assembly to achieved the desired residence time.

The volume of the inlet and outlet chambers is preferably designed so as to allow for the required residence times of between 1/20 of a minute and 1 minute. In order to achieve these residence times, the inlet chamber is preferably sized so as to have volume equal to the area of the porous pumping element multiplied by a width of between about 0.4 cm and about 3 cm. The outlet chamber can also be similarly sized. The fluid inlets and outlets from these chambers are preferably designed so as to induce some mixing of the fluids within these chambers. The fluid in the inlet chamber is considered well mixed when the standard deviation of the average pH of the fluid in the inlet chamber is preferably less than 3 pH points. More preferably the standard deviation of the pH is less than 2 pH points. Most preferably the standard deviation of the pH is less than 1 pH point. In order for the fluid in the inlet chamber to become well mixed, the average fluid velocity of the fluid entering the inlet chamber at the inlet port is of high average velocity. High average velocity is preferably greater than 10 cm/sec. More preferably, high average velocity is greater than 20 cm/sec. Most preferably, high average velocity is greater than 25 cm/sec.

Referring to Figures 3A and 4A, the bottom housing portion 102A preferably includes two ports 128, 130 which are configured to hold the inlet and outlet electrical contacts 112A, 112B, respectively. In particular, the contact port 130 extends from the cavity 106 and preferably protrudes out from the bottom surface 118A. In addition, the contact port 128 protrudes out from the bottom surface 118A and preferably extends through the body of the bottom housing portion 102A to the lip 118B of the bottom housing portion 102A. As shown with respect to Figures 3A and 4, the outlet electrical contact 112B fits within the electrical port 130, whereby the outlet electrical contact 112B is in contact with the outlet electrode 112B'. In addition, the inlet electrical contact 112A fits within the electrical port 128, whereby the inlet electrical contact 112A is in contact with the inlet electrode 112A'.

The housing 102 of the present pump 100 is made of a material such that electrical contact provided to the pumping element 104 does not short-out the pump 100. Preferably, the housing 102 is made of an insulating material, including but not limited to glass, ceramic, plastic, polymer or a combination thereof. Alternatively, the housing 102 is made of any appropriate metal which has its inside surface coated with any of the above specified insulating materials.

It is also preferable that the materials selected for the pump, and the other components in the system 10 (Figure 1), are compatible with the fluid used in the system 10. As described above, the fluid used in the system 10 is preferably water-based. More preferably, the fluid is a buffered water solution with a high pH. With such a fluid, there are materials that are likely to corrode or decompose, such as Aluminum. However, there are many metals, ceramics and glasses that are compatible with a high pH buffered water solution. Preferred metals include, but are not limited to, copper, titanium, stainless steel, platinum, silver, gold, niobium, and nickel. Preferred ceramics include, but are not limited to, silicon nitride, titania, alumina, and silica. Preferred glasses include, but are not limited to, silica, borosilicate, and vycor.

Certain pumping element materials, such as silica, in combination with fluids of certain pH range are known to have a negative zeta potential. When this combination of fluid and pump material are used, fluid flow moves from anode to cathode. Alternatively, other pumping element materials, such as alumina, when combined with fluid of a certain pH range, exhibit positive zeta potential. When this combination of fluid and pump material are used, fluid flow moves from cathode to the anode.

As know in the art, a result of operating an electroosmosis pump is that O_2 is generated at the inlet electrode. Some of the generated O_2 takes the form of dissolved O_2 in the fluid. An undesired consequence is that the dissolved O_2 can react with organic materials, such as epoxy, at any location in the cooling loop of system 10 (Figure 1). If the dissolved O_2 does react with the organic material, the O_2 is removed from the system which leaves an excess H_2, gradually contributing to pressure increases inside the system. This effect can be limited by reducing or limiting the fraction of the inside surface of the entire system that is organic. In one embodiment of the present invention, the pump assembly 100, 200 is comprised solely from non-reacting materials, such a glass, sealing glass, metals, and ceramics. In this case, solder and/or sealing glass are used as joining materials, instead of using epoxy. In another embodiment, where the use of epoxy is desired, the areas inside the pump assembly in which the epoxy is exposed to the fluid are limited by proper design. The exposed areas can also be coated with a non-reactive coating and/or the exposed surface can be pre-treated so that it is already oxidized and therefore inert to further oxidation.

It is also contemplated that other fluids can be used within the system 10, and the materials used for the components of the system 10 are any materials compatible with the selected fluid, e.g. any material with negligible or no corrosion or decomposition in the presence of the selected fluid.

Referring back to Figure 5A, an inlet fluid tube 138 is coupled to the inlet fluid port 126. Preferably, a sealing collar 144 is positioned between the inner surface of the fluid tube 136 and the fluid port 126. The sealing collar 144 is preferably made of Tungsten or other appropriate material which has a CTE that approximately matches the material of the fluid port 126. Since the CTE of the sealing collar 144 material approximates that of the fluid port 126 material, the CTE of the sealing collar 144 material will probably not match that of the fluid tube material 138. However, the sealing collar 144 preferably includes an appropriate ductility to maintain a seal with the fluid tube 138 material regardless of the amount of expansion or contraction experienced by the fluid tube 138. The sealing collar 144 is preferably also positioned between the outlet fluid port 124 and an outlet fluid line 136. Although the sealing collar 144 is described in relation to the pump 100, it is apparent to one skilled in the art that the sealing collar 144 can also be used to couple the fluid lines and the inlet and outlet ports of the other components in the system 10 (Figure 1), including but not limited to the heat exchanger 12 and the heat rejecter 20.

The sealing collar 144 is applied between the fluid tube 136, 138 and the fluid ports 124, 126 by preferably heating the fluid tube 136, 138 to a temperature whereby the fluid tube 136, 138 expands to allow a slip fit over the sealing collar 144. The sealing collar 144 is then inserted within the tube 136, 138 and the tube 136, 138 is allowed to cool and contract, forming a seal around the sealing collar 144. Prior to completing this assembly, the sealing collar 144 is coupled to the fluid port 124, 126 by any appropriate method including , but not limited to, sealing glass, solder, melting the glass, and joining with epoxy. Alternatively, the sealing collar 144 is coupled to the fluid port 124, 126 during the glass molding or pressing process of forming the housing 102. The pumping element 104 and the housing components are preferably attached using these same processes. The order of the steps of assembling the pump 100 is determined by the temperatures of the components in each step as well as the desire to protect certain elements of the pump 100 from certain temperatures. For example, if the catalyst has an upper thermal exposure limit of 400C, it is desired to carry out higher temperature assembly steps prior to the sealing of the recombination chamber 108 with the catalyst element inside.

The fluid tubes 136, 138 are preferably coupled to the fluid ports 124, 126 via the sealing collar 144, as described above. Alternatively, the fluid tubes 136, 138 are hermetically coupled to the fluid ports 124, 126 using alternative means including, but not limited to, placing a sealing material between the sealing collar and the fluid port and/or placing a sealing material between the sealing collar and the fluid tube, inserting the fluid

tube directly into the fluid port without use of the sealing collar, and inserting the fluid tube into the fluid port with a sealing material placed there between without use of the sealing collar. Examples of such sealing means are described in greater detail in the co-filed, co-pending U.S. Patent Application Serial No. __(Cool-0 2100)__, filed on ________, entitled "Hermetic Closed Loop Fluid System", which is hereby incorporated by reference.

A preferred process for assembling the pump 100 involves using sealing glass or low modulus adhesive to couple the porous pumping element 104 to the cavity 106 within the housing 102 as well as to couple the seals between the housing ports 124,126 and the sealing collars 144. Electrical feedthroughs are preferably formed in the next step. Following, the housing components 102A, 102B are combined with the electrodes 112A', 112B' and catalyst within. Following, the housing 102 is sealed using a low-temperature solder reflow or an epoxy seal. The fluid tubes 136, 138 are then preferably heated and sealed around the sealing collars 144.

Figure 5B illustrates a cross sectional view of the alternative pump assembly 200 in accordance with the present invention. In the alternative pump assembly 200, the inlet electrode 212A' (not shown) is coupled to the top surface of the pumping element 204, and the outlet electrode 212B' (not shown) is coupled to the bottom surface of the pumping element 204. As shown with respect to Figures 2B, 4B and 5B, the outlet electrical contact 212B fits within the electrical port 230 to make contact with the outlet electrode 212B', whereby the outlet electrode 212B' is in contact with the outlet side of the pumping element 204. In addition, the inlet electrical contact 212A fits within the electrical port 228 to make contact with the inlet electrode 212A', whereby the inlet electrode 212A' in contact with the inlet side of the pumping element 104.

Figure 6A illustrates a cross sectional view of the electrical contacts 112A, 112B used in the preferred electroosmotic pump assembly 100 of the present invention. As shown in Figure 6A, the inlet electrical contact 112A is positioned within the inlet port 128 and the outlet electrical contact 112B is positioned within the outlet port 130. Preferably the electrical contacts 112A, 112B are positioned in the housing portion 102A through the same outer surface, such as the bottom surface 118A (Figure 4A), to allow the pump 100 to fit in smaller areas within the electronic device. Alternatively, the electrical contacts 112A, 112B are positioned in the pump 100 through different outer surfaces of the housings 102A, 102B.

Similar to the fluid tubes 136, 138, the electrical contacts 112A, 112B are preferably made of copper which has a CTE that typically mismatches the CTE of the housing 102 material. Thus, expansion of the copper electrical contacts 112A, 112B at a rate faster than

the housing 102 material will cause the electrical contacts 112A, 112B to press against the inner walls of their respective ports and improve the pressure of the seal between the housing 102 and the electrical contacts 112A, 112B. In an extreme case, the increased pressure exceeds the material strength of the housing material and leads to cracks forming in the housing 102. In contrast, expansion of the housing 102 material at a rate faster than that of the electrical contacts 112A, 112B will cause a gap in the seal between each electrical contact 112A, 112B and its respective electrical contact port 128, 130, thereby also jeopardizing the sealed environment within the pump 100 and system 10 (Figure 1). To allow the electrical contacts 112A, 112B and housing 102 to thermally expand at different rates while maintaining the sealed environment of the pump 100 and system 10, the sealing collar 144 is preferably positioned between the inner surface of the contact ports 128, 130 and the electrical contact 112A, 112B. The sealing collar 144 is preferably made of tungsten or other appropriate material which has a CTE that approximately matches the housing 102 material. The sealing collar 144 also has an appropriate ductility to provide a tolerance buffer between the electrical contact 112A, 112B and the electrical contact ports 128,130 such that the electrical contacts 112A, 112B and ports 128, 130 are allowed to expand and contract at their respective rates without forfeiting the sealed environment within the housing 102.

The sealing collar 144 is preferably secured to the electrical contacts 112A, 112B and the contact ports 128, 130 by using a sealing glass therebetween. Alternatively, the sealing collar 144 is secured to the electrical contact 112 and the ports 128, 130 using solder. Alternatively, instead of using a sealing collar 144 between the contacts 112A, 112B and the ports 128, 130 housing, the electrical contacts 112A, 112B themselves may be made of tungsten or any other appropriate material, such that the electrical contact 112A, 112B expands along with the housing 102 and maintains the environment within the pump 100. Alternatively, sealing methods similar to those described above in relation to coupling the fluid tubes 136, 138 to the fluid ports 124, 126 can be used to seal the electrical contacts 112A, 112B to the housing 102.

Figure 6B illustrates a cross sectional view of the electrical contacts used in the alternative pump assembly 200 in accordance with the present invention. As shown in Figure 6B, the inlet electrical contact 212A is positioned within the inlet port 228 and is coupled to the on-frit inlet electrode 212A', and the outlet electrical contact 212B is positioned within the outlet port 230 and is coupled to the on-frit outlet electrode 212B'.

It is understood that the aforementioned description related to the preferred pump assembly 100 of Figures 2A, 3A, 4A, 5A, and 6A apply similarly to the alternative pump

assembly 200 of Figures 2B, 3B, 4B, 5B, and 6B with the exception of the on-frit electrodes of pump 200 versus the off-frit electrodes of pump 100.

Figure 7A illustrates a cut-away view of the preferred pump assembly 100 with the inlet electrical contact 112A coupled to an off-frit electrode 146 preferably disposed on the inner surface of the housing lid 102B, where the off-frit electrode 146 is preferably positioned a predetermined distance from the pumping assembly 104. As shown in Figure 7A, the inlet electrical contact 112A is coupled to the off-frit electrode 146 by a solder or conductive epoxy 148. Preferably, an epoxy 150 is disposed over the electrical contact 112A and attaching material 148 to passivate and thereby protect the attaching material 148. Similarly, the outlet electrical contact 112B (not shown) is coupled to a second off-frit electrode (not shown) preferably disposed on the inner surface of the bottom housing portion 102A, where the second off-frit electrode is preferably positioned a predetermined distance from the pumping assembly 104. The outlet electrical contact 112B is coupled to the second off-frit electrode by a solder or conductive epoxy, and an epoxy is preferably disposed over the electrical contact 112B and attaching material.

Figure 7B illustrates a cut-away view of the alternative pump assembly 200 with the inlet electrical contact 212A coupled thereto in accordance with the present invention. As shown in Figure 7B, the inlet electrical contact 212A is coupled to an on-frit electrode 246 disposed on the surface of the pumping element 204 by a solder or conductive epoxy 248. More details regarding the on-frit electrode 246 are shown and described in co-pending U.S. patent application Serial No. 10/669,495, filed September 23, 2003, entitled "Micro-fabricated Electrokinetic Pump with On-frit Electrode", which is hereby incorporated by reference. In the case of a solder being used as the attaching material 248, electrical current applied to the electrical contact 212A causes the solder joint to corrode. Alternatively, in the case of a conductive epoxy being used as the attaching material 248, electrical current applied to the electrical contact 212A causes silver corrosion to occur. To prevent the corrosion from occurring, an epoxy 250 is disposed on top of the electrical contact 212A and attaching material 248 to passivate and thereby protect the attaching material 248. The same applies to the outlet electrical contact 212B (not shown) as to the inlet electrical contact 212A.

As described in detail above, when an epoxy is used as part of the pump assembly, such as conductive epoxy 148, 248 and epoxy 150, 250 (Figures 7A and 7B), it is preferred that the epoxy is coated with a non-reactive coating or the epoxy is pre-treated such that an epoxy area exposed to the fluid within the system is inert to further oxidation.

Operation of the electroosmotic pump 100 will now be discussed in detail with reference to Figure 5A. As shown by the arrows in Figure 5A, fluid enters the pump 100 preferably through the fluid inlet port 126, whereby the fluid flows into the fluid inlet chamber 142. The pumping element 104 positioned below the fluid inlet chamber 142 draws substantially all of the fluid from the fluid inlet chamber 142 through the individual fluid pathways in the pumping element 104 by electroosmosis. The fluid is pumped through the pumping element 104, whereby the fluid flows to the outlet fluid chamber 140 below the pumping element 104. The fluid pumped into the fluid outlet chamber 140 flows to the outlet port 124. As stated above, the inlet port 126 extends through the body of the bottom housing portion 102A and does not allow fluid flowing through the inlet port to mix or come into contact with the fluid entering the fluid outlet chamber 140. The fluid then exits out of the outlet port 124 through the fluid line 136 to the downstream components in the loop 10.

In operation of the preferred embodiment, in which the pumping element has a negative zeta potential, the recombination chamber 108 preferably stores excess oxygen generated on the low pressure side of the pumping element 104 which does not travel with the circulating fluid. Thus, as excess oxygen is generated within the pump 100, the gas flows naturally to the recombination chamber 108 and remains within the chamber 108. Meanwhile, excess hydrogen is generated on the high pressure side of the pumping element 104. The excess hydrogen is carried along with the fluid flow and enters the recombination chamber 108, wherein the excess hydrogen gas and oxygen gas recombines into water which is output from the pump 100. The alternative electroosmotic pump 200 operates in a similar fashion as that described above in relation to pump 100.

Although the pump assembly has been described such that the inlet and outlet electrodes are either both off-frit electrodes (pump assembly 100) or both on-frit electrodes (pump assembly 200), the pump assembly can also be configured such that one of the electrodes is an on-frit electrode and the other electrode is an off-frit electrode.

Figure 8 illustrates a cross sectional view of an alternative pump assembly 300. The pump assembly 300 includes a means for allowing the gas generated in the outlet electrode chamber to be brought directly to the inlet chamber without passing through the entire loop of system 10 (Figure 1). A semipermeable element 321 which allows the passage of gas without allowing the passage of fluid is positioned near the top of the outlet chamber 340. As such, H_2 gas generated in the outlet chamber 340 is allowed to rise to this semipermeable element 321, and travel directly to the inlet chamber 342. The H_2 gas rises with the O_2 generated in the inlet chamber 342 to the recombination chamber 308. The semipermeable

element 321 can be comprised of many materials, including a porous structure, a hydrophobic mesh material, or any other material or structure which preferentially allows gas to pass without allowing fluids to pass. Several examples of such a bypass are described in the pending U.S. Patent Application No. 2003/0164231, published on September 4, 2003, and entitled "Electroosmotic Microchannel Cooling System", which is hereby incorporated by reference. The semipermeable element 321 is mounted in the housing 302A using low-modulus adhesive, sealing glass, or by any other means described herein.

Although embodiments of the electrokinetic pump described herein are directed to a single inlet chamber and a single outlet chamber, it is understood that the electrokinetic pump can include one or more inlet chambers, one or more pumping elements, and one or more outlet chambers. Each inlet chamber can include one or more fluid inlet ports.

The figures are provided for illustrative purposes and to aid in the understanding of the present invention. Certain descriptive terms, such as up, down, below and above, are used relative to the figures being described. Such descriptions are not intended to limit the operational orientation of the present invention.

The present invention has been described in terms of specific embodiments incorporating details to facilitate the understanding of the principles of construction and operation of the invention. Such reference herein to specific embodiments and details thereof is not intended to limit the scope of the claims appended hereto. It will be apparent to those skilled in the art that modifications may be made in the embodiment chosen for illustration without departing from the spirit and scope of the invention.

CLAIMS

What is claimed is:

1. An electroosmotic pump comprising:
   a. a fluid chamber;
   b. a pumping element for pumping fluid therethrough, the pumping element positioned to segment the fluid chamber into an inlet chamber including a fluid inlet port and an outlet chamber including a fluid outlet port;
   c. an inlet electrode positioned within the inlet chamber and a predetermined distance from a first surface of the pumping element;
   d. an outlet electrode positioned within the outlet chamber; and
   e. means for providing electrical voltage to the inlet electrode and the outlet electrode to produce an electrical field therebetween, wherein the means for providing is coupled to the inlet electrode and the outlet electrode.

2. The electroosmotic pump according to claim 1 wherein the predetermined distance that the inlet electrode is positioned from the first surface is in a range of about 0.05 mm to about 5.0 mm.

3. The electroosmotic pump according to claim 1 wherein the outlet electrode is positioned a predetermined distance from a second surface of the pumping element.

4. The electroosmotic pump according to claim 3 wherein the predetermined distance that the outlet electrode is positioned from the second surface is in a range of about 0.05 mm to about 5.0 mm.

5. The electroosmotic pump according to claim 1 wherein the outlet electrode is positioned on a second surface of the pumping element.

6. The electroosmotic pump according to claim 1 wherein a residence time of the inlet chamber is in a range of about 1/20 of a minute to about 1 minute.

7. The electroosmotic pump according to claim 6 wherein a volume of the inlet chamber

is equal to an area of the pumping element multiplied by a width of between about 0.4 cm and about 3.0 cm.

8. The electroosmotic pump according to claim 1 wherein the electroosmotic pump is manufactured using one or more materials comprising metal, glass, ceramic, plastic, or a combination thereof.

9. The electroosmotic pump according to claim 8 wherein the one or more materials are coupled by one or more sealing materials.

10. The electroosmotic pump according to claim 8 wherein the one or more sealing materials comprise solder, sealing glass, low modulus adhesives, or a combination thereof.

11. The electroosmotic pump according to claim 10 wherein low modulus adhesives seal the pumping element to a housing of the electroosmotic pump.

12. The electroosmotic pump according to claim 1 wherein the electroosmotic pump is manufactured using one or more pump materials such that each pump material is compatible with the fluid, or such that the one or more pump materials that are not compatible with the fluid are overcoated with a compatible material.

13. The electroosmotic pump according to claim 12 wherein the fluid comprises a buffered water solution.

14. The electroosmotic pump according to claim 13 wherein the one or more pump materials comprise insulating materials that are compatible with buffered water solutions.

15. The electroosmotic pump according to claim 14 wherein the pump material is selected from a group consisting of silicon nitride, titania, alumina, silica, borosilicate, vycor, and plastic.

16. The electroosmotic pump according to claim 1 wherein the pumping element exhibits

a negative zeta potential in the presence of the fluid and the inlet electrode is an anode electrode and the outlet electrode is a cathode electrode.

17. The electroosmotic pump according to claim 16 wherein a material of the anode electrode is selected from the group consisting of platinum, platinum clad niobium, platinum plated titanium, platinum clad tantalum, graphite, glassy carbon, mixed metal oxide coating on titanium, silver-impregnated ink, and dimensionally-stable anode material.

18. The electroosmotic pump according to claim 17 wherein the mixed metal oxide coating on titanium includes an iridium and tantalum oxide coating on titanium.

19. The electroosmotic pump according to claim 17 wherein the dimensionally-stable anode material includes one from the group consisting of conducting iridium oxide coating on titanium and ruthenium oxide coating on titanium

20. The electroosmotic pump according to claim 16 wherein a material of the cathode electrode is selected from a group consisting of platinum, copper, platinum plated titanium, stainless steel, graphite, gold, plated silver, silver-impregnated ink, and glassy carbon.

21. The electroosmotic pump according to claim 1 wherein the pumping element exhibits a positive zeta potential in the presence of the fluid and the inlet electrode is a cathode electrode and the outlet electrode is an anode electrode.

22. The electroosmotic pump according to claim 21 wherein a material of the anode electrode is selected from the group consisting of platinum, platinum clad niobium, platinum plated titanium, platinum clad tantalum, graphite, glassy carbon, mixed metal oxide coating on titanium, silver-impregnated ink, and dimensionally-stable anode material.

23. The electroosmotic pump according to claim 22 wherein the mixed metal oxide coating on titanium includes an iridium and tantalum oxide coating on titanium.

24. The electroosmotic pump according to claim 22 wherein the dimensionally-stable anode material includes one from the group consisting of conducting iridium oxide coating on titanium and ruthenium oxide coating on titanium

25. The electroosmotic pump according to claim 21 wherein a material of the cathode electrode is selected from a group consisting of platinum, copper, platinum plated titanium, stainless steel, graphite, gold, plated silver, silver-impregnated ink, and glassy carbon.

26. The electroosmotic pump according to claim 1 further comprising one or more inlet chambers, one or more pumping elements, and one or more outlet chambers, wherein each inlet chamber includes one or more fluid inlet ports.

27. The electroosmotic pump according to claim 1 further comprising a recombination chamber coupled to the inlet chamber to recombine an inlet chamber gas and an outlet chamber gas.

28. The electroosmotic pump according to claim 1 wherein the inlet port to the inlet chamber is configured and positioned such that fluid entering the inlet chamber becomes well mixed.

29. The electroosmotic pump according to claim 28 wherein the fluid is well mixed by providing the fluid from the inlet port into the inlet chamber at a high average velocity.

30. The electroosmotic pump according to claim 29 wherein the high average velocity of the fluid entering the inlet chamber at the inlet port is greater than about 25 centimeters per second.

31. An electroosmotic pump comprising:
   a. a fluid chamber;
   b. a pumping element for pumping fluid therethrough, the pumping element positioned to segment the fluid chamber into an inlet chamber including a fluid inlet port and an outlet chamber including a fluid outlet port, wherein a

size of the inlet chamber is proportional to a predetermined residence time of the inlet chamber;

c. an inlet electrode positioned within the inlet chamber;

d. an outlet electrode positioned within the outlet chamber; and

e. means for providing electrical voltage to the inlet electrode and the outlet electrode to produce an electrical field therebetween, wherein the means for providing is coupled to the inlet electrode and the outlet electrode.

32. The electroosmotic pump according to claim 31 wherein the residence time of the inlet chamber is in a range of about 1/20 of a minute to about 1 minute.

33. The electroosmotic pump according to claim 32 wherein a volume of the inlet chamber is equal to an area of the pumping element multiplied by a width of between about 0.4 cm and about 3.0 cm.

34. The electroosmotic pump according to claim 31 wherein the inlet electrode is positioned a predetermined distance from a first surface of the pumping element.

35. The electroosmotic pump according to claim 34 wherein the predetermined distance that the inlet electrode is positioned from the first surface is in a range of about 0.05 mm to about 5.0 mm.

36. The electroosmotic pump according to claim 31 wherein the outlet electrode is positioned a predetermined distance from a second surface of the pumping element.

37. The electroosmotic pump according to claim 36 wherein the predetermined distance that the outlet electrode is positioned from the second surface is in a range of about 0.05 mm to about 5.0 mm.

38. The electroosmotic pump according to claim 31 wherein the outlet electrode is positioned on a second surface of the pumping element.

39. The electroosmotic pump according to claim 31 consisting of one or more materials that are non-reactive to oxygen.

40. The electroosmotic pump according to claim 31 wherein the electroosmotic pump is manufactured using one or more materials comprising metal, glass, ceramic, plastic, or a combination thereof.

41. The electroosmotic pump according to claim 40 wherein the one or more materials are coupled by one or more sealing materials.

42. The electroosmotic pump according to claim 41 wherein the one or more sealing materials comprise solder, sealing glass, low modulus adhesives, or a combination thereof.

43. The electroosmotic pump according to claim 42 wherein low modulus adhesives seal the pumping element to a housing of the electroosmotic pump.

44. The electroosmotic pump according to claim 31 wherein the electroosmotic pump is manufactured using one or more pump materials such that each pump material is compatible with the fluid, or such that the one or more pump materials that are not compatible with the fluid are overcoated with a compatible material.

45. The electroosmotic pump according to claim 44 wherein the fluid comprises a buffered water solution.

46. The electroosmotic pump according to claim 45 wherein the one or more pump materials comprise insulating materials that are compatible with buffered water solutions.

47. The electroosmotic pump according to claim 46 wherein the pump material is selected from a group consisting of silicon nitride, titania, alumina, silica, borosilicate, vycor, and plastic.

48. The electroosmotic pump according to claim 31 wherein the pumping element exhibits a negative zeta potential in the presence of the fluid and the inlet electrode is an anode electrode and the outlet electrode is a cathode electrode.

49. The electroosmotic pump according to claim 48 wherein a material of the anode electrode is selected from the group consisting of platinum, platinum clad niobium, platinum plated titanium, platinum clad tantalum, graphite, glassy carbon, mixed metal oxide coating on titanium, silver-impregnated ink, and dimensionally-stable anode material.

50. The electroosmotic pump according to claim 49 wherein the mixed metal oxide coating on titanium includes an iridium and tantalum oxide coating on titanium.

51. The electroosmotic pump according to claim 49 wherein the dimensionally-stable anode material includes one from the group consisting of conducting iridium oxide coating on titanium and ruthenium oxide coating on titanium.

52. The electroosmotic pump according to claim 48 wherein a material of the cathode electrode is selected from a group consisting of platinum, copper, platinum plated titanium, stainless steel, graphite, gold, plated silver, silver-impregnated ink, and glassy carbon.

53. The electroosmotic pump according to claim 31 wherein the pumping element exhibits a positive zeta potential in the presence of the fluid and the inlet electrode is a cathode electrode and the outlet electrode is an anode electrode.

54. The electroosmotic pump according to claim 53 wherein a material of the anode electrode is selected from the group consisting of platinum, platinum clad niobium, platinum plated titanium, platinum clad tantalum, graphite, glassy carbon, mixed metal oxide coating on titanium, silver-impregnated ink, and dimensionally-stable anode material.

55. The electroosmotic pump according to claim 54 wherein the mixed metal oxide coating on titanium includes an iridium and tantalum oxide coating on titanium.

56. The electroosmotic pump according to claim 54 wherein the dimensionally-stable anode material includes one from the group consisting of conducting iridium oxide coating on titanium and ruthenium oxide coating on titanium.

57. The electroosmotic pump according to claim 53 wherein a material of the cathode electrode is selected from a group consisting of platinum, copper, platinum plated titanium, stainless steel, graphite, gold, plated silver, silver-impregnated ink, and glassy carbon.

58. The electroosmotic pump according to claim 31 further comprising one or more inlet chambers, one or more pumping elements, and one or more outlet chambers, wherein each inlet chamber includes one or more fluid inlet ports.

59. The electroosmotic pump according to claim 31 further comprising a recombination chamber coupled to the inlet chamber to recombine an inlet chamber gas and an outlet chamber gas.

60. The electroosmotic pump according to claim 31 wherein the inlet port to the inlet chamber is configured and positioned such that fluid entering the inlet chamber becomes well mixed.

61. The electroosmotic pump according to claim 60 wherein the fluid is well mixed by providing the fluid from the inlet port into the inlet chamber at a high average velocity.

62. The electroosmotic pump according to claim 61 wherein the high average velocity of the fluid entering the inlet chamber at the inlet port is greater than about 25 centimeters per second.

63. An electroosmotic pump comprising:

a. a fluid chamber;

b. a pumping element for pumping fluid therethrough, the pumping element positioned to segment the fluid chamber into an inlet chamber including a fluid inlet port and an outlet chamber including a fluid outlet port;

c. a gas permeable element to allow passage of a gas from the outlet chamber to the inlet chamber while preventing the passage of the fluid therethrough;

d. an inlet electrode positioned within the inlet chamber and a predetermined distance from a first surface of the pumping element;

e. an outlet electrode positioned within the outlet chamber; and

f. means for providing electrical voltage to the inlet electrode and the outlet electrode to produce an electrical field therebetween, wherein the means for providing is coupled to the inlet electrode and the outlet electrode.

64. The electroosmotic pump according to claim 63 wherein the gas permeable element allows the passage of an outlet chamber gas from the outlet chamber to the inlet chamber.

65. The electroosmotic pump according to claim 64 wherein the outlet chamber gas is predominately hydrogen.

66. The electroosmotic pump according to claim 64 wherein the outlet chamber gas is predominately oxygen.

67. The electroosmotic pump according to claim 63 wherein the predetermined distance that the inlet electrode is positioned from the first surface is in a range of about 0.05 mm to about 5.0 mm.

68. The electroosmotic pump according to claim 63 wherein the outlet electrode is positioned a predetermined distance from a second surface of the pumping element.

69. The electroosmotic pump according to claim 68 wherein the predetermined distance that the outlet electrode is positioned from the second surface is in a range of about 0.05 mm to about 5.0 mm.

70. The electroosmotic pump according to claim 63 wherein the outlet electrode is positioned on a second surface of the pumping element.

71. The electroosmotic pump according to claim 63 wherein a residence time of the inlet

chamber is in a range of about 1/20 of a minute to about 1 minute.

72. The electroosmotic pump according to claim 63 wherein a volume of the inlet chamber is equal to an area of the pumping element multiplied by a width of between about 0.4 cm and about 3.0 cm.

73. The electroosmotic pump according to claim 63 wherein the electroosmotic pump is manufactured using one or more materials comprising metal, glass, ceramic, plastic, or a combination thereof.

74. The electroosmotic pump according to claim 73 wherein the one or more materials are coupled by one or more sealing materials.

75. The electroosmotic pump according to claim 74 wherein the one or more sealing materials comprise solder, sealing glass, low modulus adhesives, or a combination thereof.

76. The electroosmotic pump according to claim 75 wherein low modulus adhesives seal the pumping element to a housing of the electroosmotic pump.

77. The electroosmotic pump according to claim 63 wherein the electroosmotic pump is manufactured using one or more pump materials such that each pump material is compatible with the fluid, or such that the one or more pump materials that are not compatible with the fluid are overcoated with a compatible material.

78. The electroosmotic pump according to claim 77 wherein the fluid comprises a buffered water solution.

79. The electroosmotic pump according to claim 78 wherein the one or more pump materials comprise insulating materials that are compatible with buffered water solutions.

80. The electroosmotic pump according to claim 79 wherein the pump material is selected from a group consisting of silicon nitride, titania, alumina, silica,

borosilicate, vycor, and plastic.

81. The electroosmotic pump according to claim 63 wherein the pumping element exhibits a negative zeta potential in the presence of the fluid and the inlet electrode is an anode electrode and the outlet electrode is a cathode electrode.

82. The electroosmotic pump according to claim 81 wherein a material of the anode electrode is selected from the group consisting of platinum, platinum clad niobium, platinum plated titanium, platinum clad tantalum, graphite, glassy carbon, mixed metal oxide coating on titanium, silver-impregnated ink, and dimensionally-stable anode material.

83. The electroosmotic pump according to claim 82 wherein the mixed metal oxide coating on titanium includes an iridium and tantalum oxide coating on titanium.

84. The electroosmotic pump according to claim 82 wherein the dimensionally-stable anode material includes one from the group consisting of conducting iridium oxide coating on titanium and ruthenium oxide coating on titanium

85. The electroosmotic pump according to claim 81 wherein a material of the cathode electrode is selected from a group consisting of platinum, copper, platinum plated titanium, stainless steel, graphite, gold, plated silver, silver-impregnated ink, and glassy carbon.

86. The electroosmotic pump according to claim 63 wherein the pumping element exhibits a positive zeta potential in the presence of the fluid and the inlet electrode is a cathode electrode and the outlet electrode is an anode electrode.

87. The electroosmotic pump according to claim 86 wherein a material of the anode electrode is selected from the group consisting of platinum, platinum clad niobium, platinum plated titanium, platinum clad tantalum, graphite, glassy carbon, mixed metal oxide coating on titanium, silver-impregnated ink, and dimensionally-stable anode material.

88. The electroosmotic pump according to claim 87 wherein the mixed metal oxide coating on titanium includes an iridium and tantalum oxide coating on titanium.

89. The electroosmotic pump according to claim 87 wherein the dimensionally-stable anode material includes one from the group consisting of conducting iridium oxide coating on titanium and ruthenium oxide coating on titanium

90. The electroosmotic pump according to claim 86 wherein a material of the cathode electrode is selected from a group consisting of platinum, copper, platinum plated titanium, stainless steel, graphite, gold, plated silver, silver-impregnated ink, and glassy carbon.

91. The electroosmotic pump according to claim 63 further comprising one or more inlet chambers, one or more pumping elements, and one or more outlet chambers, wherein each inlet chamber includes one or more fluid inlet ports.

92. The electroosmotic pump according to claim 63 further comprising a recombination chamber coupled to the inlet chamber to recombine an inlet chamber gas and an outlet chamber gas.

93. The electroosmotic pump according to claim 63 wherein the inlet port to the inlet chamber is configured and positioned such that fluid entering the inlet chamber becomes well mixed.

94. The electroosmotic pump according to claim 93 wherein the fluid is well mixed by providing the fluid from the inlet port into the inlet chamber at a high average velocity.

95. The electroosmotic pump according to claim 94 wherein the high average velocity of the fluid entering the inlet chamber at the inlet port is greater than about 25 centimeters per second.

96. A pump assembly comprising:

a. a structure adapted to house a pumping element;

b. a plurality of fluid lines coupled to the structure; and

c. a ductile material configured between the structure and each fluid line, wherein the ductile material has a thermal expansion characteristic substantially similar with a structure material.

97. The pump assembly according to claim 96 wherein the structure further comprises a first electrical port configured to provide a first electrical contact to a first side of the pumping element.

98. The pump assembly according to claim 97 further comprising the ductile material positioned between the first electrical contact and the first electrical port.

99. The pump assembly according to claim 97 further comprising:

a. an adhesive material for coupling the first electrical contact to the first side; and

b. a passivation layer applied to the adhesive material, wherein the passivation layer protects the adhesive material from migration.

100. The pump assembly according to claim 96 wherein a substantial portion of the pumping element includes non-parallel apertures.

101. The pump assembly according to claim 100 further comprises an epoxy material applied to a perimeter surface of the pumping element, wherein the epoxy has an expansion characteristic matching a pumping element material.

102. The pump assembly according to claim 97 wherein the structure further comprises a second electrical port configured to provide a second electrical contact to the second side.

103. The pump assembly according to claim 102 further comprising the ductile material positioned between the second electrical contact and the second electrical port.

104. The pump assembly according to claim 102 wherein the first electrical port and the second electrical port are configured on a same outer surface plane of the structure.

105. The pump assembly according to claim 102 wherein the first electrical port and the second electrical port are configured on a different outer surface plane of the structure.

106. The pump assembly according to claim 96 wherein the pumping element further comprises a first side and a second side, wherein the first side is associated with a fluid inlet area in the structure and the second side is associated with a fluid outlet area in the structure, the plurality of fluid lines for circulating fluid from the fluid inlet area to the fluid outlet area.

107. The pump assembly according to claim 96 wherein the structure further comprises a first outer surface and a second outer surface, wherein a first fluid line and a second fluid line of the plurality of fluid lines are coupled to the structure on the first outer surface.

108. The pump assembly according to claim 96 wherein the structure further comprises a first outer surface and a second outer surface, wherein a first fluid lie of the plurality of fluid lines is coupled to the first outer surface and a second fluid line of the plurality of fluid lines is coupled to the second outer surface.

109. The pump assembly according to claim 106 wherein the structure further comprises:

a. a base having a receptacle for holding the pumping element wherein a first fluid line is in communication with the fluid inlet area and a second fluid line is in communication with the fluid outlet area; and

b. a lid coupled to the base and configured to provide a sealed engagement thereto.

110. The pump assembly according to claim 109 wherein the base further comprises a cavity for recombining excess hydrogen and oxygen gases into water.

111. The pump assembly according to claim 96 wherein the ductile material is Tungsten.

112. The pump assembly according to claim 96 wherein the pumping element is made of borosilicate glass.

113. The pump assembly according to claim 96 wherein the fluid lines are made of Copper.

114. The pump assembly according to claim 102 wherein the first and second electrical contacts are made of Copper.

115. The pump assembly according to claim 102 wherein the first and second electrical contacts are made of Tungsten.

116. A closed loop system for cooling a circuit comprising:

a. at least one heat exchanger in contact with the circuit having a plurality of heat exchange fluid ports coupled to one or more fluid lines for cooling the circuit; and

b. at least one pump assembly coupled to the heat exchanger comprising:

i. a structure adapted to house a pumping element, the structure having a plurality of pump fluid ports coupled to the fluid lines; and

ii. a ductile material configured between the pump fluid ports and each corresponding fluid line, wherein the ductile material has a thermal expansion characteristic substantially similar with a structure material.

117. The closed loop system according to claim 116 further comprising at least one heat rejecter having a plurality of heat rejecter fluid ports coupled to the fluid lines.

118. The closed loop system according to claim 117 wherein the ductile material is configured between the plurality of fluid lines and the heat rejecter fluid ports, the ductile material for sealing the heat rejecter.

119. The closed loop system according to claim 116 wherein the ductile material is configured between the plurality of fluid lines and the heat exchanger fluid ports, the ductile material for sealing the heat exchanger.

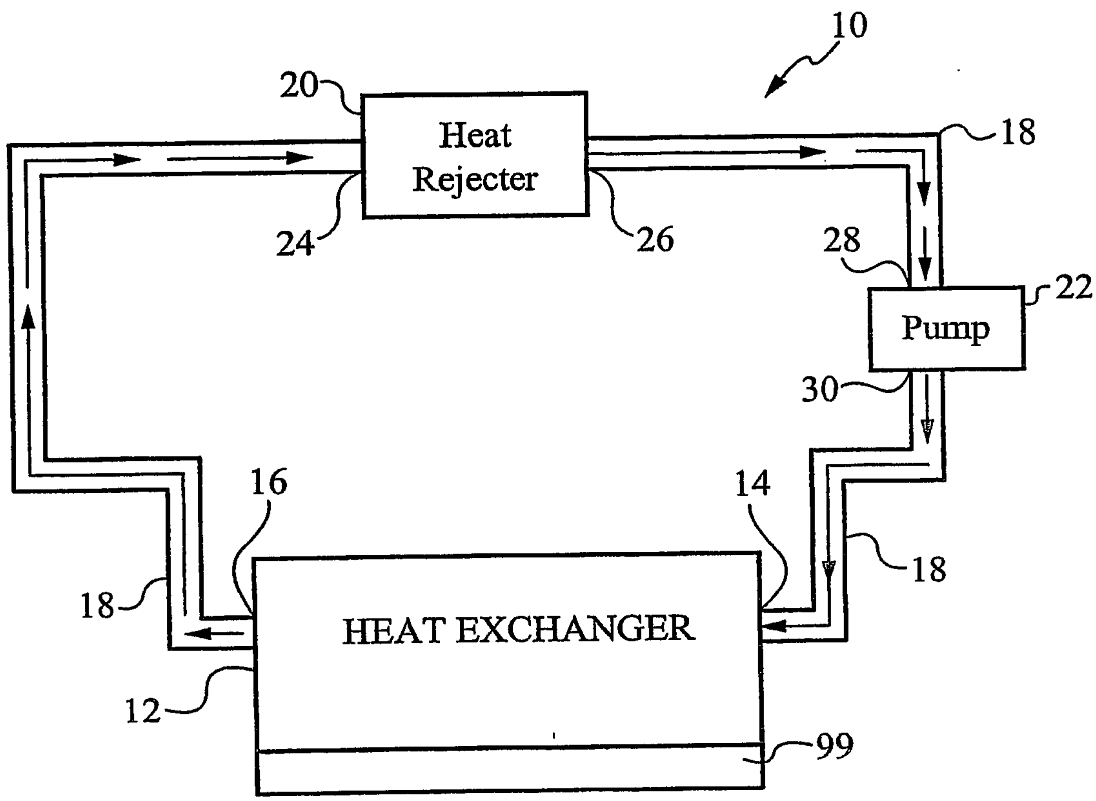
10
20
Heat
Rejecter
18
24
26
28
22
Pump
30
16
14
18
18
HEAT EXCHANGER
12
99

Fig. 1

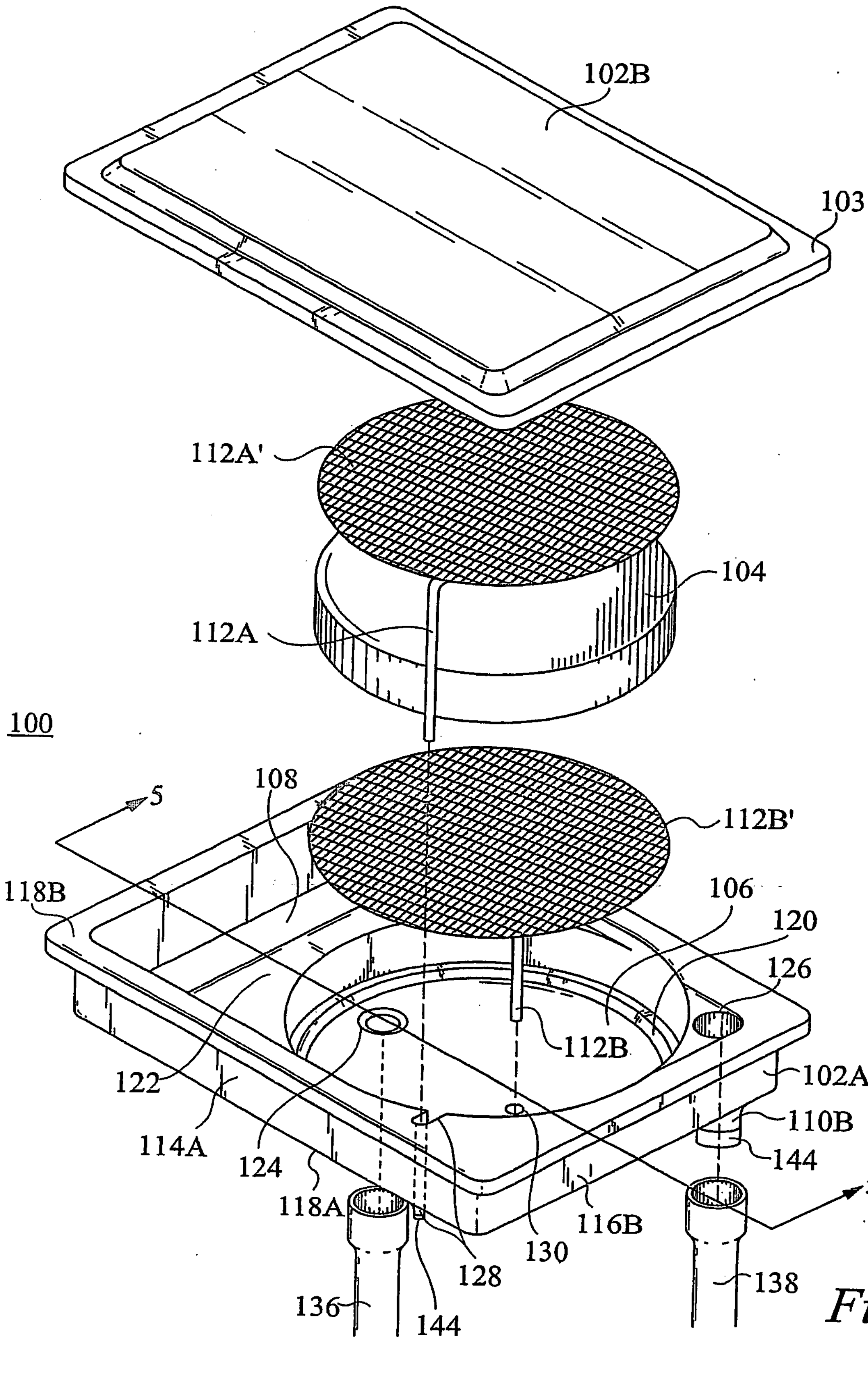
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Fig. 2A

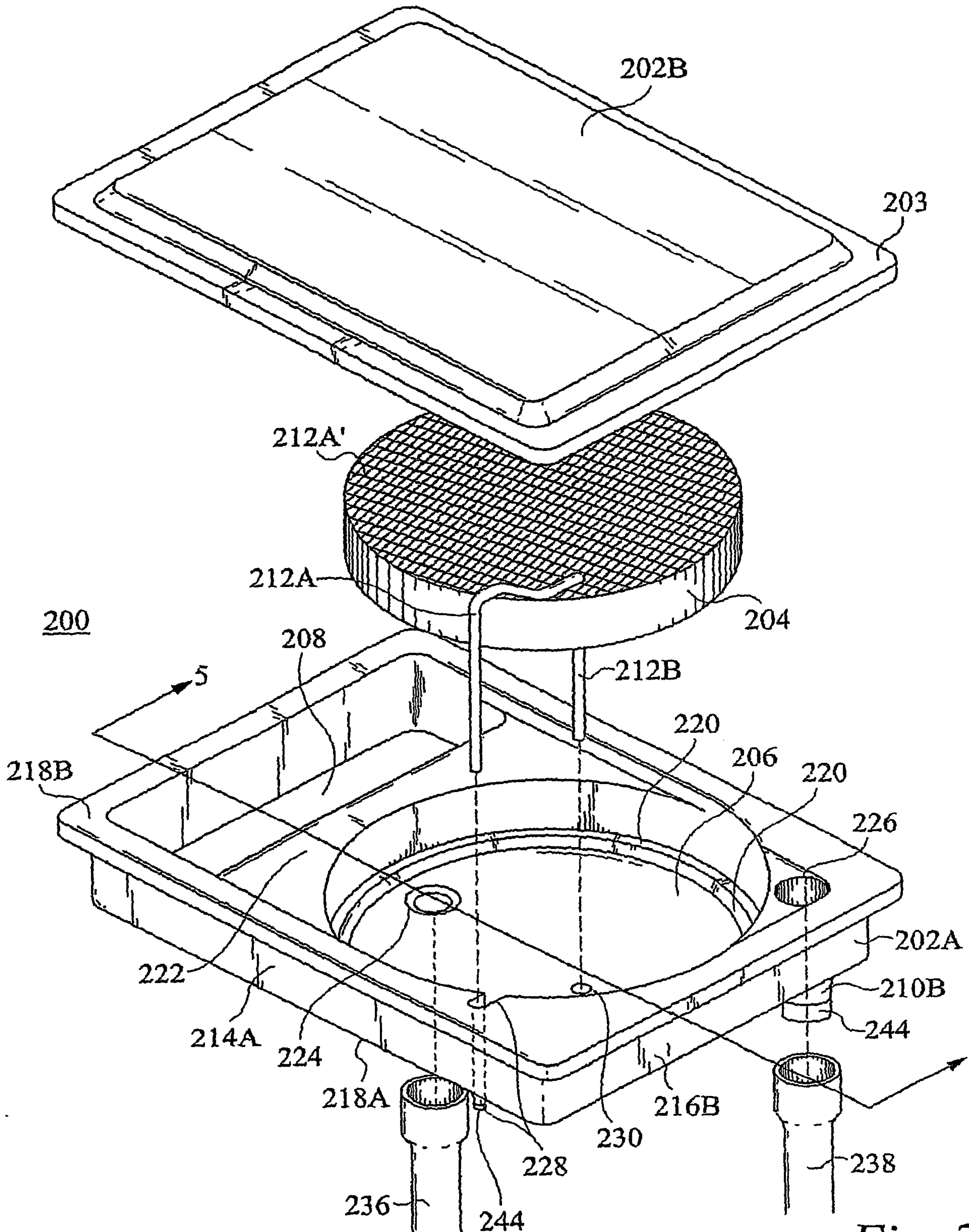
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Fig. 2B

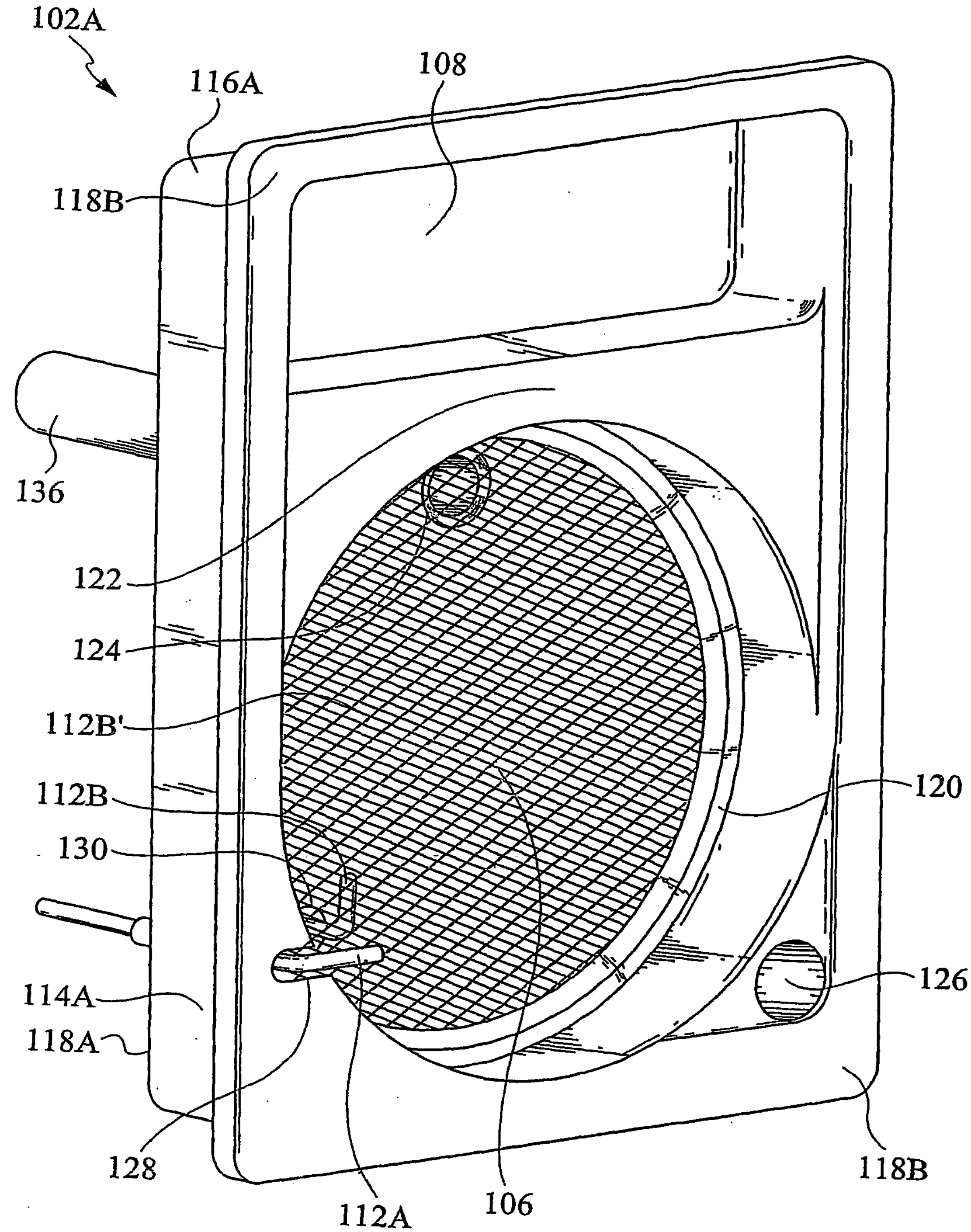
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Fig. 3A

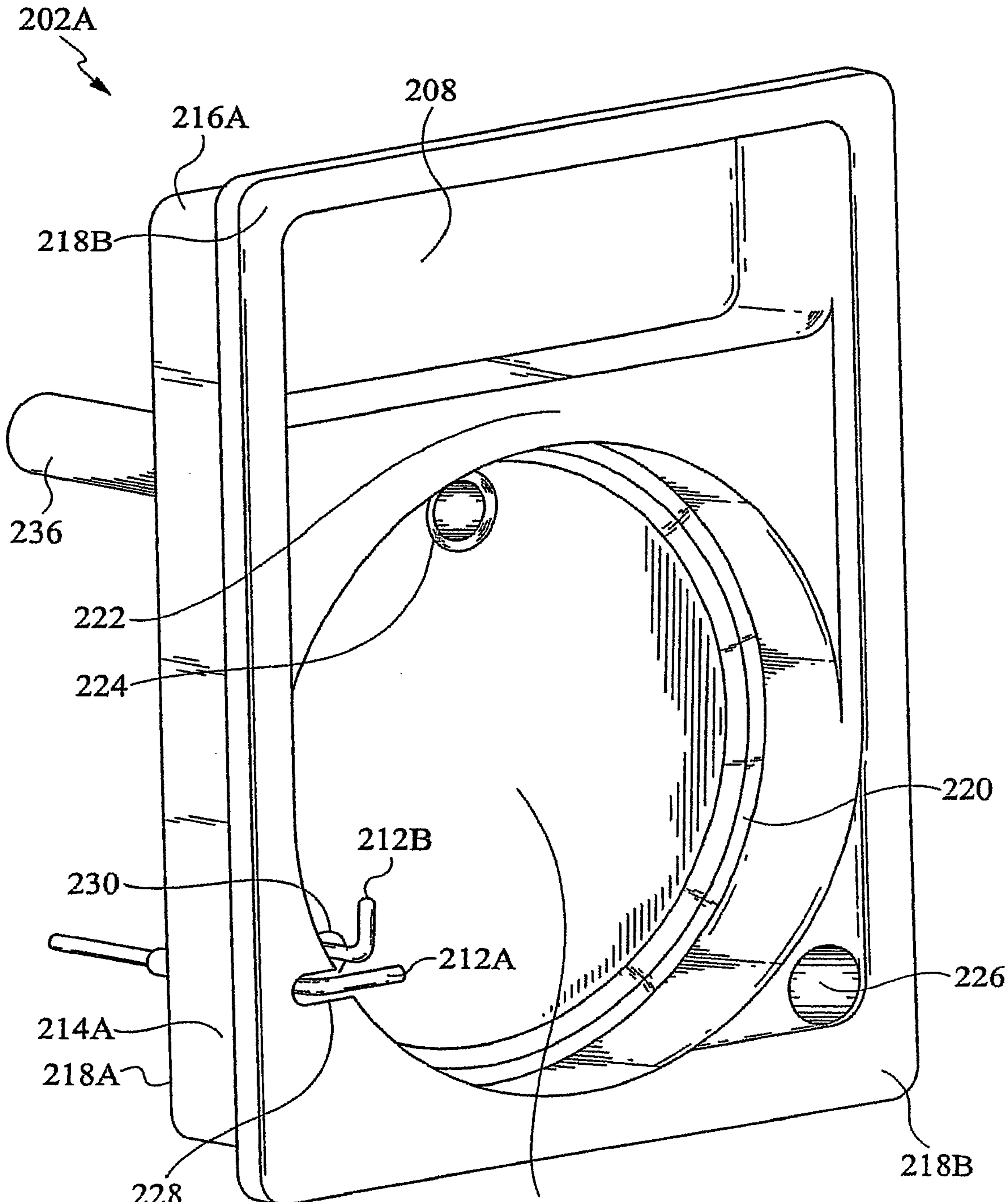
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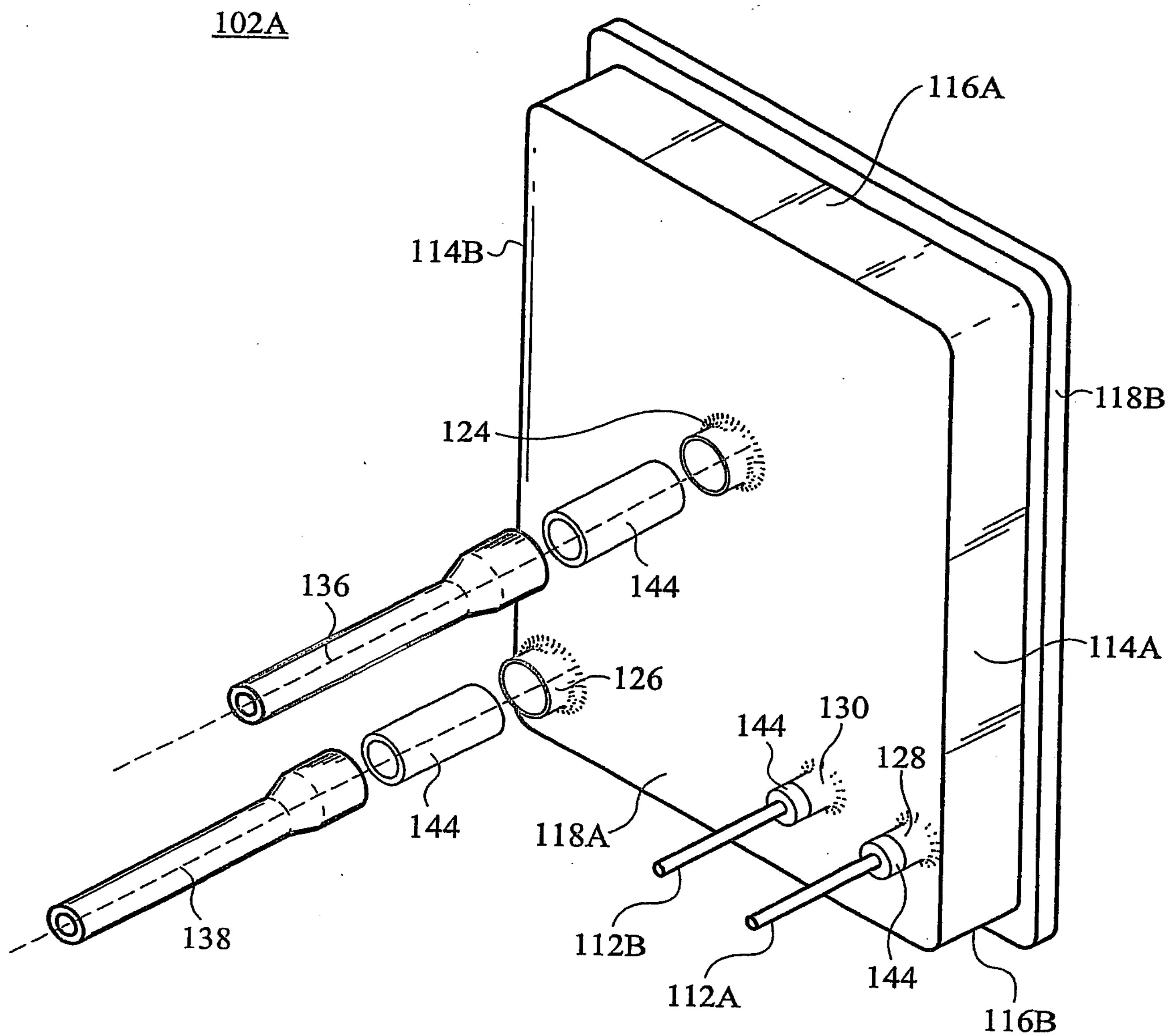
Fig. 3B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116B

Fig. 4A

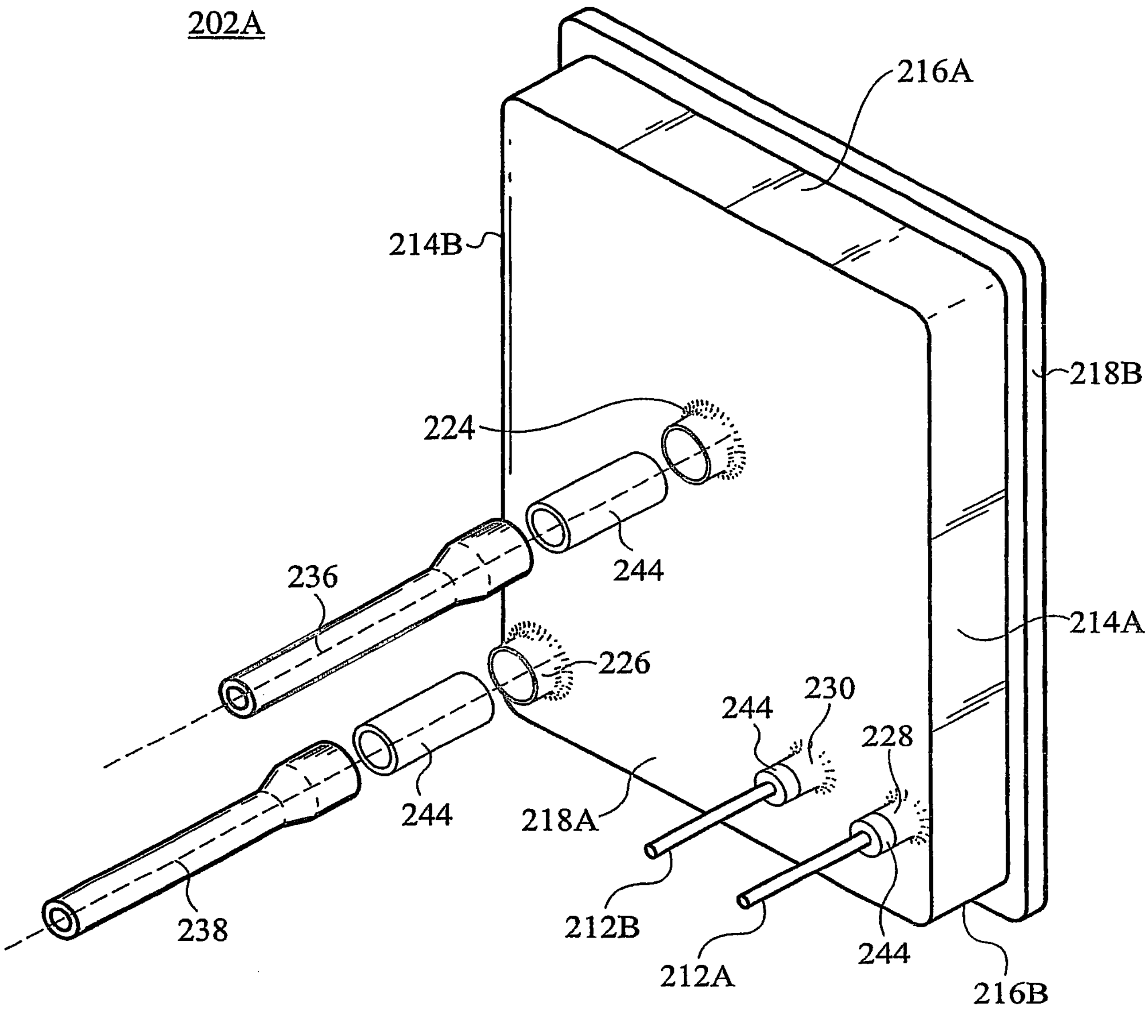
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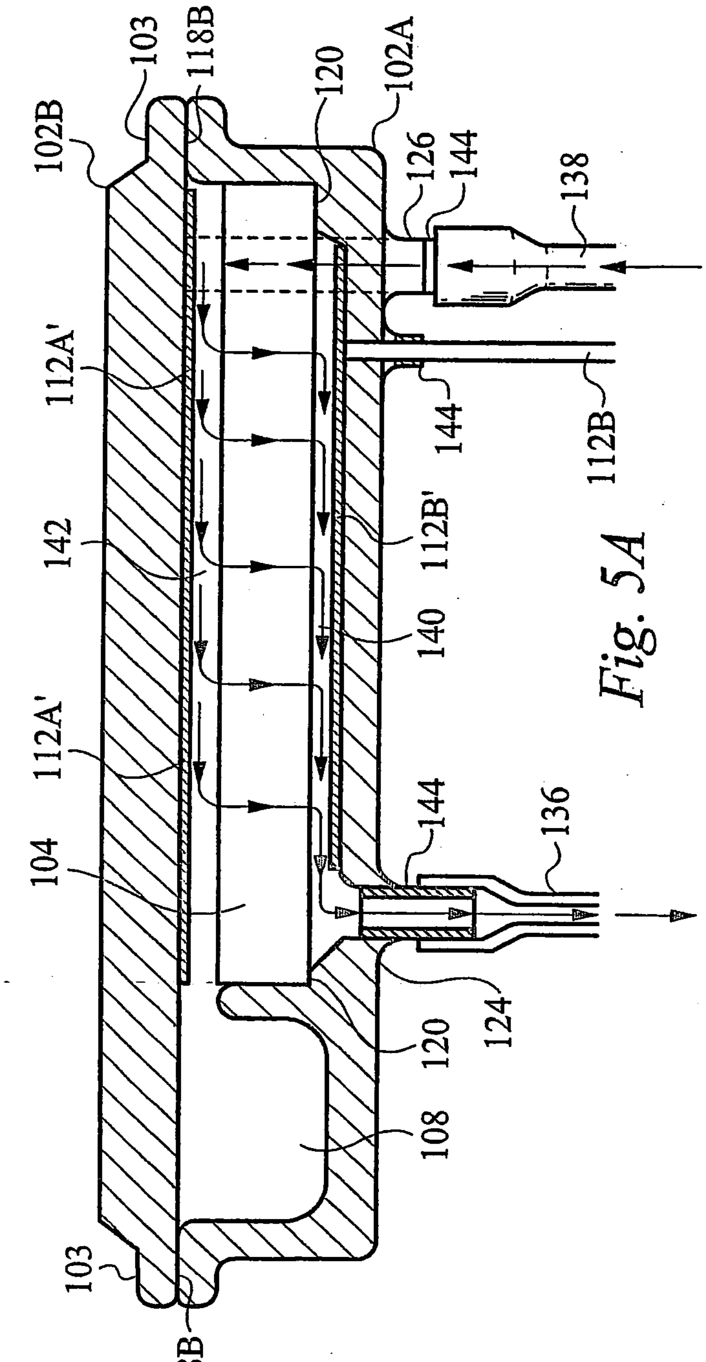
Fig. 4B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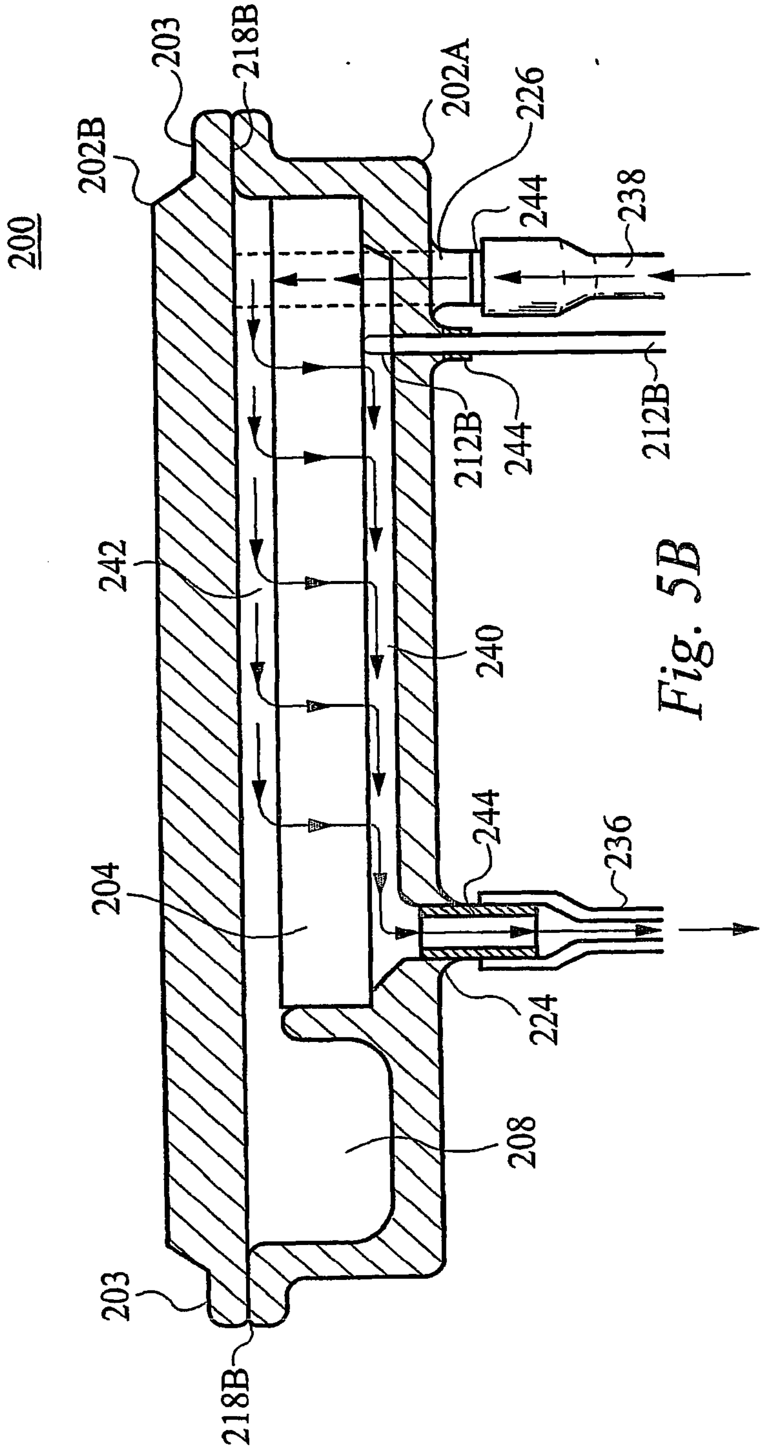
108
103
118B

Fig. 5A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218B

Fig. 5B

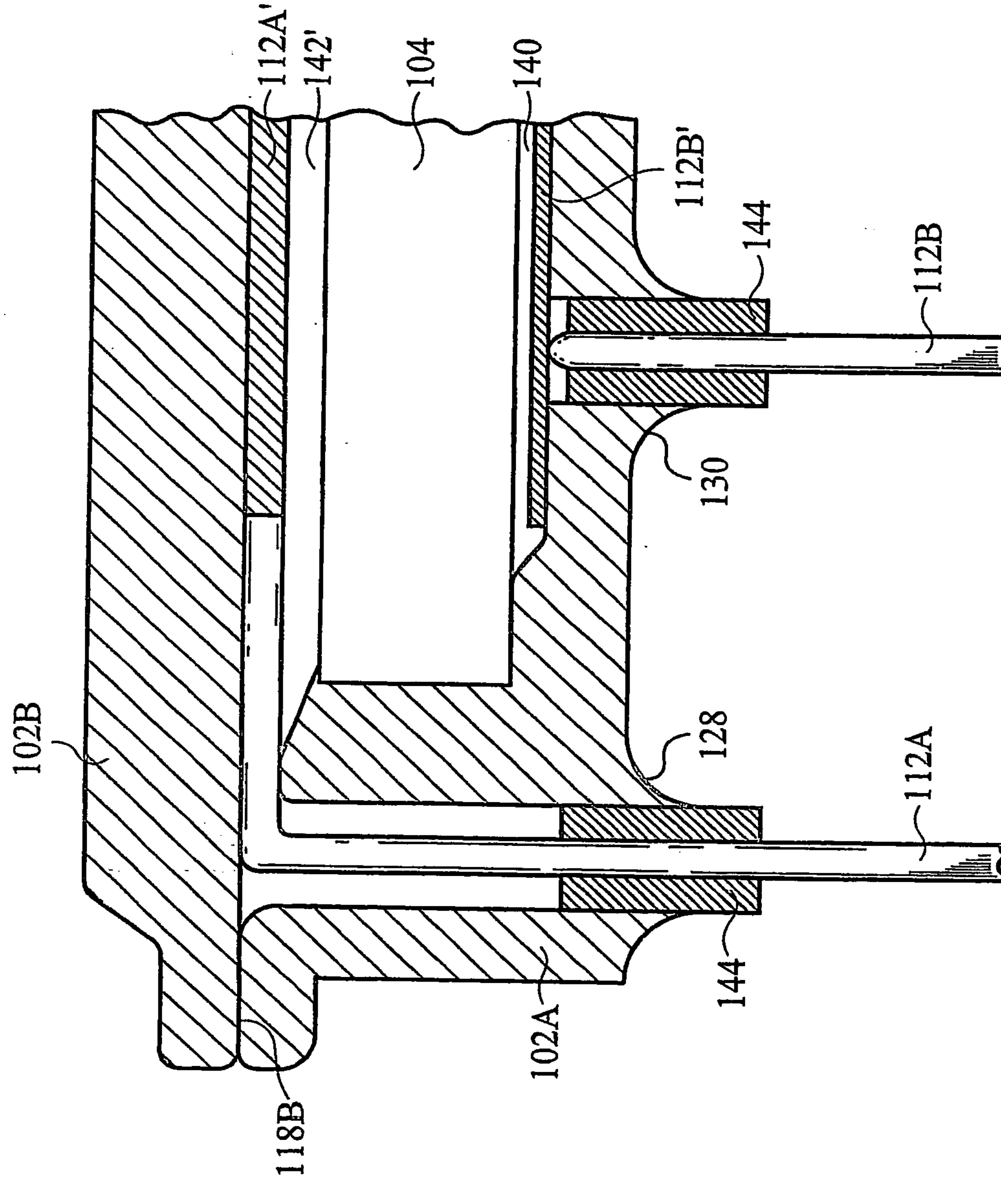


Fig. 6A

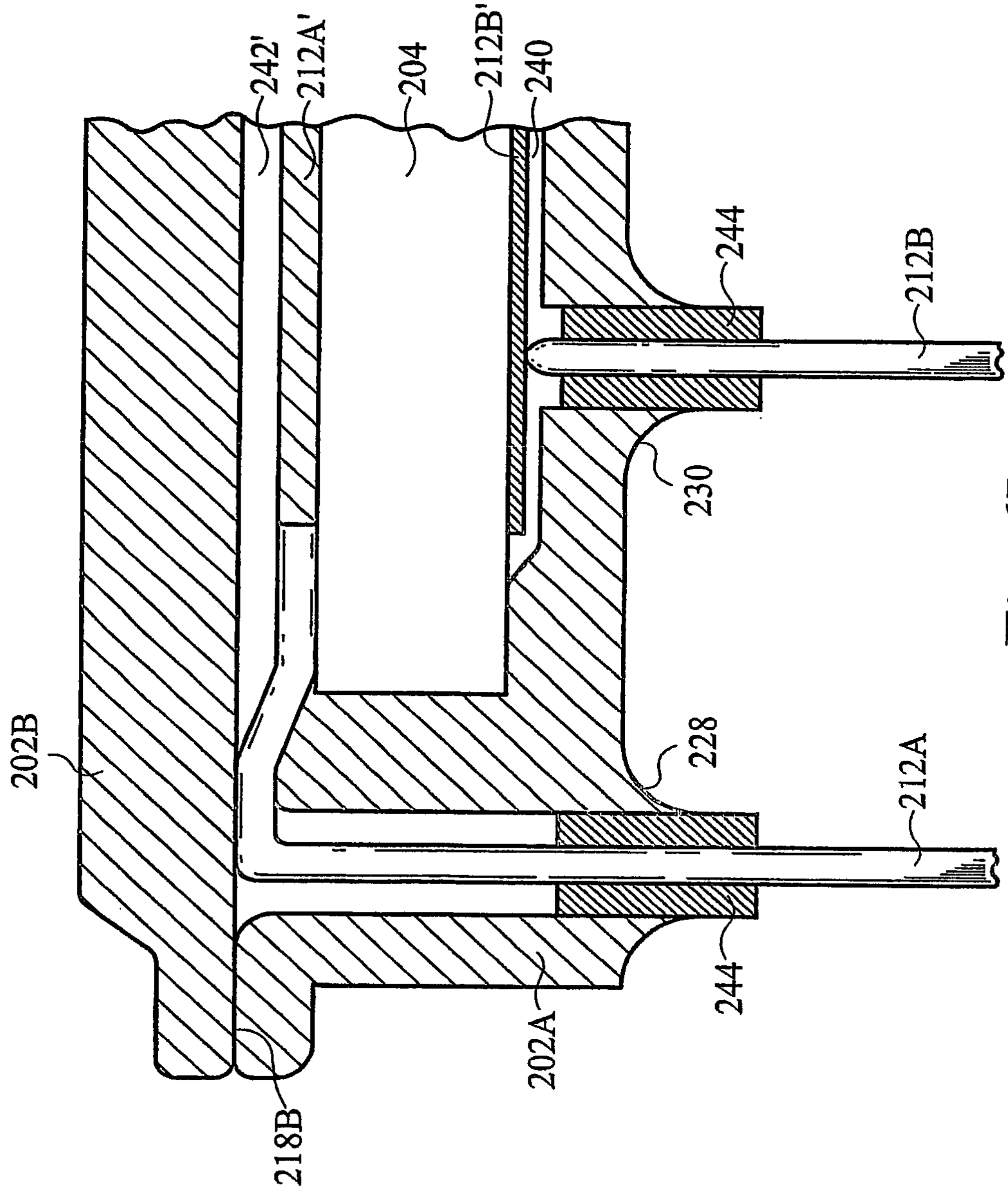


Fig. 6B

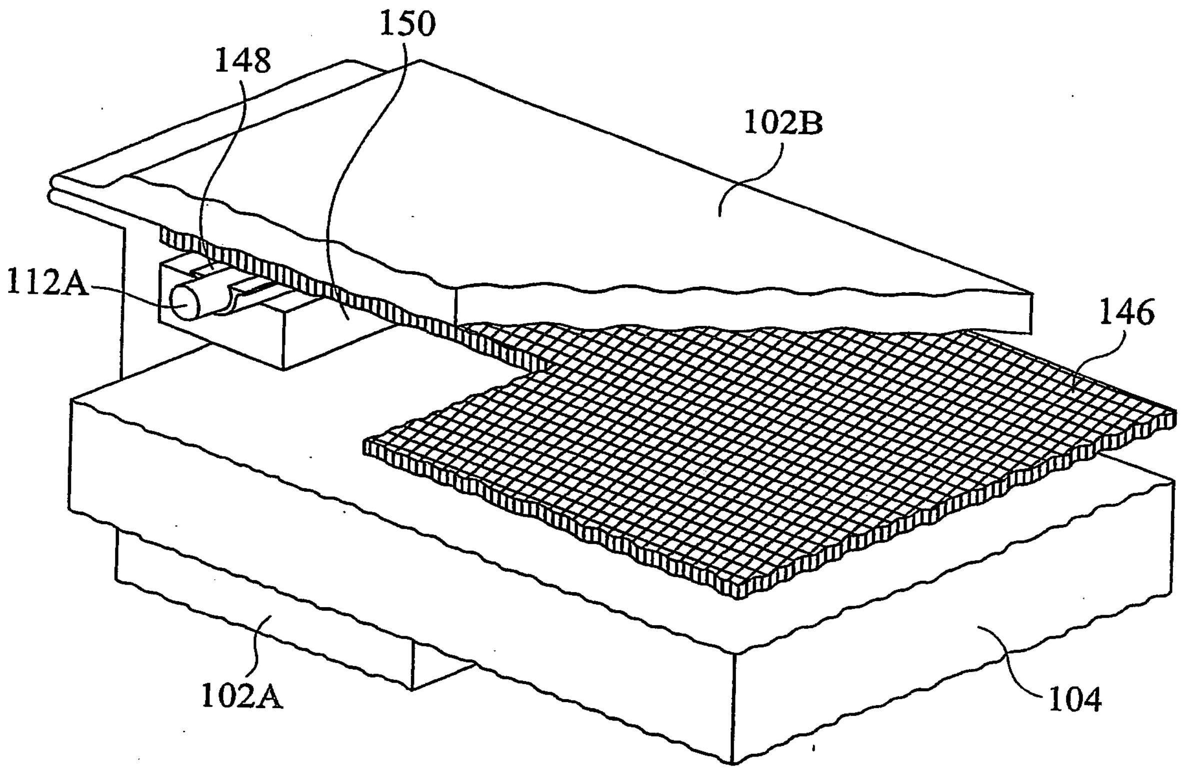


Fig. 7A

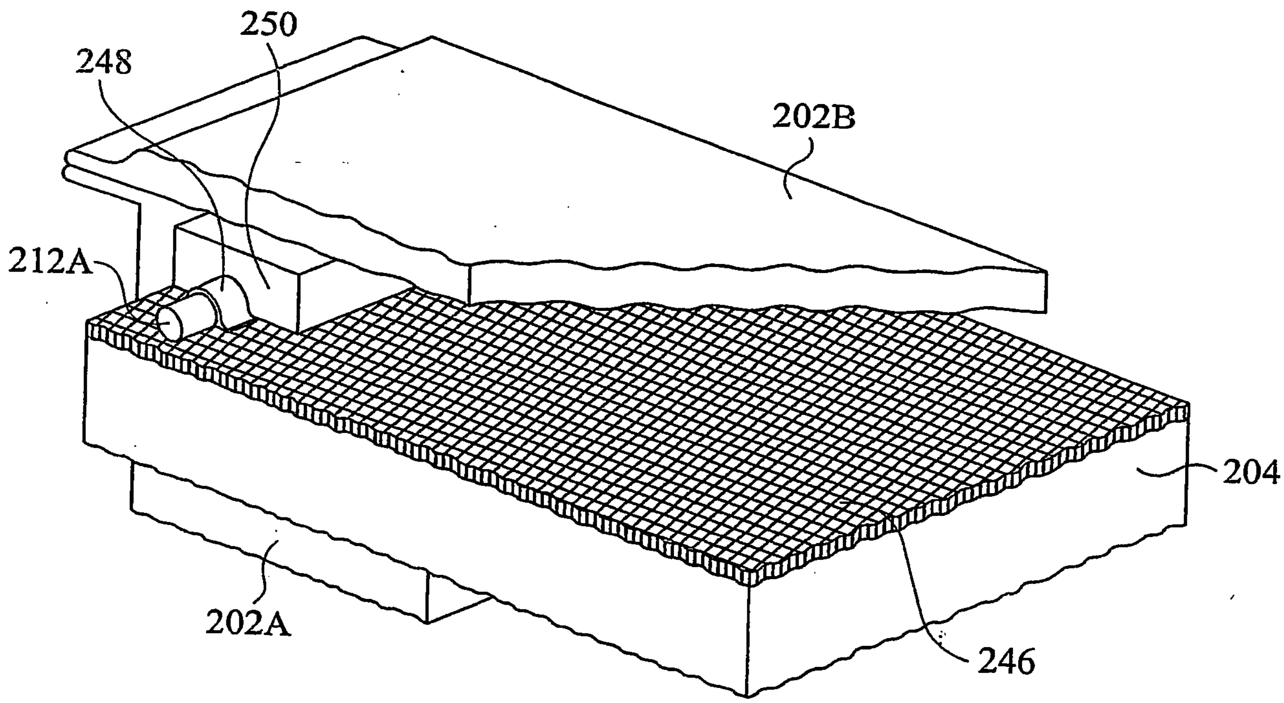
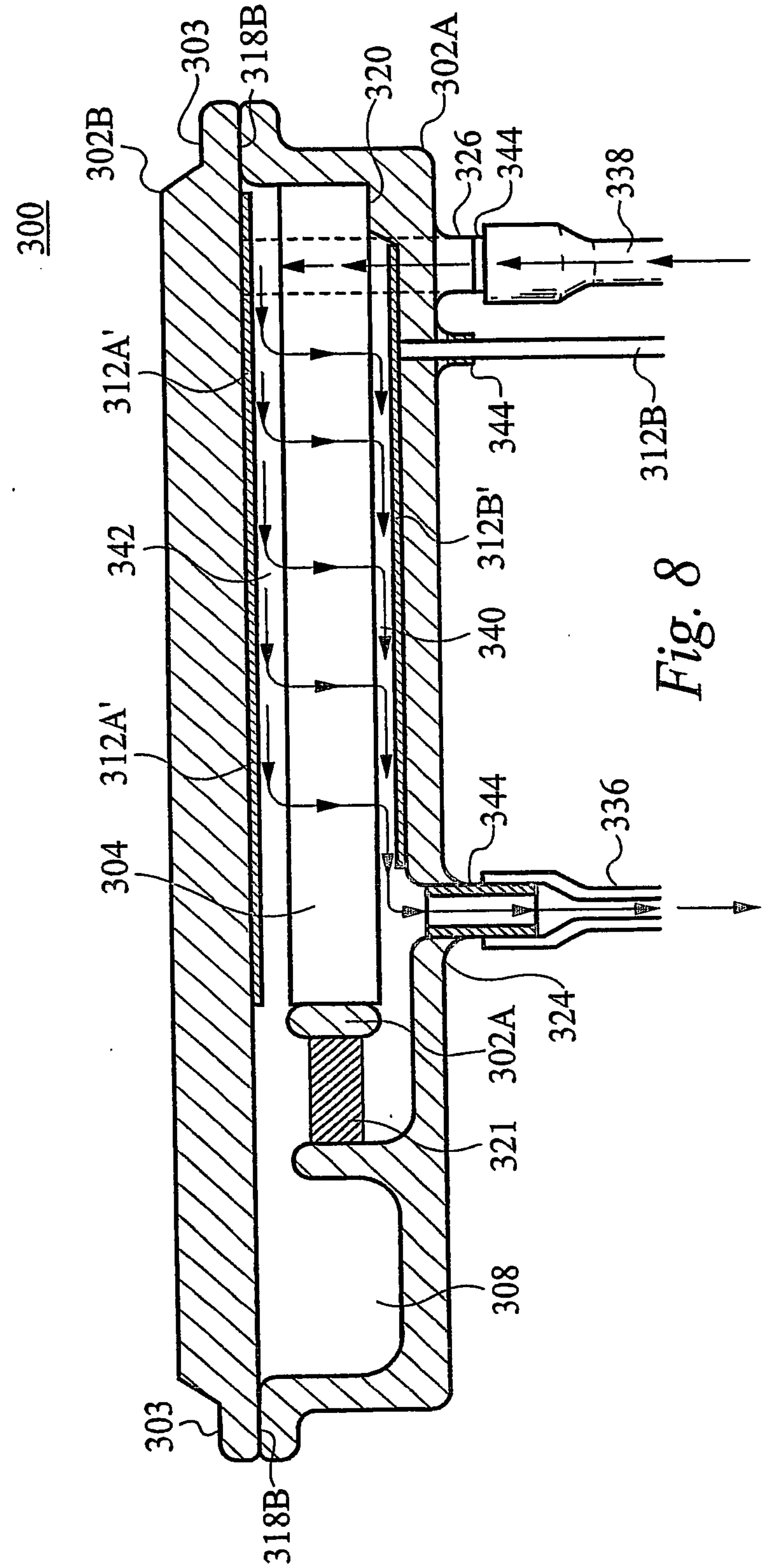


Fig. 7B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318B

Fig. 8